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ORIGINAL PAPER

Forest multifunctionality is not resilient to intensive forestry

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Abstract

There is ample evidence that intensive management of ecosystems causes declines in biodiversity as well as in multiple ecosystem services, i.e., in multifunctionality. However, less is known about the permanence and reversibility of these responses. To gain insight into whether multifunctionality can be sustained under intensive management, we developed a framework building on the concept of resilience: a system's ability to avoid displacement and to return or transform to a desired state. We applied it to test the ability of forest multifunctionality to persist during and recover from intensive management for timber production in a boreal forest. Using forest growth simulations and multiobjective optimization, we created alternative future paths where the forest was managed for maximal timber production, for forest multifunctionality, or first maximal timber production and then multifunctionality. We show that forest multifunctionality is substantially diminished under intensive forestry and recovers the slower, the longer intensive forestry has been continued. Intensive forestry thus not only reduces forest multifunctionality but hinders its recovery should management goals change, i.e., weakens its resilience. The results suggest a need to adjust ecosystem management according to long-term sustainability goals already today.

Keywords Sustainable forest management · Ecosystem services · Biodiversity · Boreal forest · Finland · Transformation capacity

Introduction

In response to global biodiversity loss, progressing climate change, and growing demand for ecosystem services, the management of production landscapes is urged to target multifunctionality: the joint production of multiple environmental, social, and economic benefits from ecosystem functions in a given land area (Bennet and Balvanera 2007; Seidl et al. 2016). Management for multifunctionality entails awareness of multiple objectives and pursuit for compromise solutions that balance conflicting objectives as well as possible (Brockerhoff et al. 2017). So far, the intensive management of ecosystems used for the production of food, raw materials, and bioenergy has led to their homogenization and simplification, and the concomitant loss of biodiversity and decline of many ecosystem services (Foley 2005; Kareiva et al. 2007; Thompson et al. 2011). In order to promote and maintain multifunctionality, the objectives that guide the management of these ecosystems have to be diversified beyond the maximal production of a single resource.

Ecosystem resilience is integral to the maintained supply of ecosystem services. Resilience describes a system's sensitivity to disturbances and its ability to absorb them without losing key functionality or shifting to an alternative stable state (Folke et al. 2004). It can be considered to have multiple aspects: resistance, recovery, and adaptative or transformation capacity (Walker and Salt 2006; Biggs et al. 2012; Oliver et al. 2015). In the context of social-ecological systems such as production landscapes, resilience is a product of both social and ecological factors: the system's response

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to and recovery from a disturbance and its capacity to adapt and transform in the face of new conditions are determined by its ecology as well as people's readiness to adjust their choices, the management options available, and their effectiveness (Peterson 2000; Cumming et al. 2013). The content given to resilience, i.e., exactly what is desired to be resilient, is a societal goal. It may be defined as the supply of ecosystem services, that is, the output of the system rather than its structure (Oliver et al. 2015). The resilience of ecosystem services thus refers to the avoidance of losses in the ecosystem service supply or to the supply's recovery to a desired level after it has been reduced, e.g., by a disturbance. In other words, the ecosystem stays within a state where the supply of ecosystem services is at the desired level.

The resilience of production ecosystems is often thought of in terms of resilience to damage caused by natural disturbances such as pest outbreaks or extreme weather (e.g., Seidl et al. 2016; Sánchez-Pinillos et al. 2019). However, in production ecosystems a major source of disturbance is the management itself: resource extraction and activities to increase the efficiency of production can change the structure and functioning of the ecosystem fundamentally (Bennet and Balvanera 2007; Edwards et al. 2014). These often sudden and recurrent modifications can cause ecosystem degradation that damages its ability to sustain ecosystem services and biodiversity (Ghazoul and Chazdon 2017). If natural succession or active management cannot reverse these impacts, the system has moved into a state of low multifunctionality that is undesirable in the long term (Oliver et al. 2018) and that can be difficult and slow to move away from even with restoration efforts (Moreno-Mateos et al. 2017). It is therefore important to consider whether the multiple ecosystem services desired from production landscapes are resilient not only against natural conditions but also against intensive management for primary production goals.

In this study, we use the concept of resilience to examine how the provision of multiple ecosystem services is sustained under management prioritizing a single production goal, and how it may recover when management is changed to prioritize multifunctionality. Our study system is a boreal production forest—an example of a presently intensively exploited ecosystem with a recognized need for multifunctionality and resilience (Moen et al. 2014; Gauthier et al. 2015). Across the boreal region, extensive tracts of forests are subjected to intensive management and harvesting with variable but often negative impacts on ecosystem services and biodiversity (Moen et al. 2014; Gauthier et al. 2015; Pohjanmies et al. 2017a). Likewise, forestry activities have been shown to reduce the supply of non-timber benefits from forests also outside the boreal zone (Başkent et al. 2011; Schwenk et al. 2012; Nolet et al. 2018). However, the effects of such management on the resilience of forest multifunctionality are virtually unexplored. This knowledge gap may lead to serious underestimation of their severity.

In order to examine the resilience of forest multifunctionality to timber-focused forestry (henceforth 'intensive forestry'), we designed a tree of alternative future scenarios for our study area, a production forest landscape in Finland. In the scenarios, the forest was managed for maximal timber production, for forest multifunctionality, or first timber production and then forest multifunctionality. Forest multifunctionality consisted of six objectives: timber production, carbon storage, bilberry yield, cowberry yield, scenic beauty, and availability of dead wood resources. We compared the values of forest multifunctionality achieved in the alternative scenarios to each other to reveal if multifunctionality is resilient to intensive forestry: if intensive forestry reduces multifunctionality, and if its recovery is affected by the length of time that intensive forestry has first been carried out. By employing forest simulations, we were able to explore the long-term outcomes of alternative management choices, and by switching the focus of management planning from timber production to multifunctionality after varying lengths of time, we were able to examine the different components of the resilience of forest multifunctionality: resistance, recovery, and transformation capacity.

Methods

Study area and forest growth simulations

Our study area is located in Central Finland. It covers 2240 ha and consists of 1475 forest stands (units of forest management) of varying age, productivity, and tree species composition. The area is a typical Finnish production forest landscape, consisting of a mosaic of stands with a fairly young age distribution. The current age of the stands ranges between 0 and 125 years with an average of 45 years. The most common tree species are pine (*Pinus sylvestris*), spruce (*Picea abies*), and birch (*Betula pendula* and *Betula pubescens*). While we have no specific information on the past management of the area, the young age distribution of the stands suggests that the area has been used extensively for production forestry, likely following even-aged rotation management that until 2014 was the legally required management system (Äijälä et al. 2014). That said, the forests in the study area are owned by private forest owners, who are known to vary in management preferences (Kuuluvainen et al. 1996). Thus, the past management has likely differed from a strict following of management recommendations, e.g., regarding the economically optimal timing of thinnings and final fellings.

We used stand-level inventory data for our study area produced by the Finnish Forest Centre as input data in the forest growth simulator SIMO (Rasinmäki et al. 2009) to create projections of the growth and development of the stands under alternative management regimes. Using forest growth models, SIMO produces projections of future stand development based on the stand's initial characteristics and the forestry operations that are applied to the stand. The timing and intensity of the operations are defined according to the simulated management regime. We simulated the development of the stands under alternative management regimes that were intended to cover a wide range of different ways to conduct and time management operations and harvests. They included rotation forestry based on clear-cut harvesting of even-aged stands (Äijälä et al. 2014), continuous cover forestry based on selective harvesting (Pukkala et al. 2012), and no management actions on the stand resulting in set-aside. Rotation forestry with clear-cut harvesting is the currently dominant mode of timber production in Finland. It consists of commercial thinnings, a clear-cut felling timed to achieve maximal value production in the stand, and regeneration of the stand after the clear-cut. In SIMO, regeneration after a clear-cut is simulated as artificial (planting), and the selection of tree species to be planted is based on rules depending on the fertility of the stand as defined in the Finnish forest management recommendations (Äijälä et al. 2014). We created several versions of rotation forestry with varying frequencies of thinning (from zero to recommended, up to three, thinnings), amounts of tree retention (from 5 to 30 trees per ha), and rotation lengths (clear-cut postponed by 5–30 years from economical optimum) for our simulations to reflect real-world variation in the implementation of the regime. Continuous cover forestry differs from rotation forestry in that it is based on repeated, selective harvesting of large trees instead of a one-time clear-cut felling, and natural regeneration instead of planting or seeding. Finally, if the stand is set-aside, no forestry activities are carried out, but the stand is left to develop naturally for the duration of the planning horizon. The implementation of the alternative management regimes in the simulator is described in more detail by Eyvindson et al. (2018). We used a planning horizon of 20 years and simulated the stands for several such planning horizons as part of the alternative future scenarios, a total of 100–180 years into the future (see section *Resilience analysis*). The simulator produced predictions of stand development at 5-year time steps, giving four such steps for each 20-year planning horizon.

Ecosystem services and biodiversity features

We produced estimates of the stand-level values of six objectives (ecosystem services or benefits to society) based on the structure and properties of each stand. The objectives included five ecosystem services: timber production, carbon storage, bilberry yield, cowberry yield, and scenic beauty. In addition, we considered one biodiversity feature, availability of dead wood resources. These objectives were chosen based on their high relevance to people and nature in Finland, as well as on the availability of data and models required to evaluate them.

Timber production was measured as net discounted harvest income (€). It was calculated as revenue from wood harvested during the planning horizon minus the costs of silvicultural operations, based on recent stumpage prices and costs (Peltola 2014). Future revenues were discounted using a moderate 1 % interest rate and were always discounted to the start of the 20-year planning horizon, so that the planning horizons would be directly comparable with each other.

Forest carbon storage has a critical role in global climate regulation and climate change mitigation (Pan et al. 2011). Carbon storage in the forest (kg) was measured as the sum of the predicted amounts of carbon fixed in living wood, dead wood and soil. Carbon fixed in harvested timber was not considered here. Carbon fixed in living and dead wood was estimated as 50% of the wood biomass. To estimate soil carbon, we used two models depending on the soil type: the Yasso07 models (Liski et al. 2005; Tuomi et al. 2009, 2011) for mineral soils, and the carbon flux models of Ojanen et al. (2014) for peatland soils. Bilberry (*Vaccinium myrtillus*) and cowberry (*Vaccinium vitis-idaea*) are the two most common wild berries in Finland with both high commercial and recreational value (Vaara et al. 2013). Bilberry yield (kg) was estimated using the models of Miina et al. (2009) and cowberry yield (kg) using the models of Turtiainen et al. (2013). Both predict species coverage and berry yield based on stand characteristics (e.g., dominant tree species, stand age, and stand basal area). In the bilberry model, berry yield increases with increasing stand age and basal area (up to certain limits) and pine dominance (Miina et al. 2009). In the cowberry model, berry yield decreases with increasing basal area and increases with pine dominance (Turtiainen et al. 2013). Forests dominate the landscape in Finland, and forest structure impacts on their perceived scenic beauty and recreational use (Silvennoinen et al. 2001; Gundersen and Frivold 2008). Scenic beauty (no unit) was measured by the index developed by Pukkala et al. (1988), which estimates the recreational and aesthetic attractiveness of a forest based on forest age, structure, and tree species composition. The index's value is increased by the size of trees and the volume of pine and deciduous trees, and decreased by the number of trees per ha.

Finally, we included the availability of dead wood resources as a biodiversity feature because lack of dead wood resources is estimated to be the most common cause of species endangerment in Finnish forests (Tikkanen et al. 2006; Rassi et al. 2010). In addition, there is strong evidence of dead wood as an indicator of broad forest-based biodiversity (Gao et al. 2015). Availability of dead wood resources was evaluated as the total amount of dead wood (m^3) multiplied by the diversity of different dead wood types, comprising different tree species and decay stages (Triviño et al. 2017). The SIMO simulator predicts the formation of dead wood and its decay by applying the models of Mäkinen et al. (2006). Diversity of dead wood types was measured with the Simpson diversity index.

Except for harvest income, we calculated the average levels of the objectives across the 5-year time steps of the 20-year simulation horizon and these averages were used in the analyses. The stand-level values were multiplied by stand area and summed together to produce landscape-level values.

Multifunctionality

We measured the ability of the forest landscape to maintain high levels of all ecosystem services and biodiversity as forest multifunctionality. We defined forest multifunctionality as a condition where the landscape-level values of all ecosystem services and biodiversity features are simultaneously as close as possible to their potential maximal levels. The definition is based on the approach proposed by Mazziotta et al. (2017) for balancing conflicting conservation objectives. To maximize forest multifunctionality, a management plan was identified for the study area where a management regime (rotation forestry, continuous cover forestry, or set-aside) was selected for each stand so that the loss in the total level of each individual objective across the landscape was minimized. A loss in an objective from its maximum under a management plan was calculated as

$$\text{loss} = \frac{\max_{\text{tot}} - \sum_i^n x_{i,j}}{\max_{\text{tot}}}$$

where x_i is the value of the objective in stand i, n is the total number of stands, j indicates a management regime selected for stand i under the management plan, and $\max_{\text{tot}}$ is the potential maximum of the objective. The potential maximal levels of the objectives were calculated by simulating the development of the stands for 100 years into the future under the alternative management regimes and identifying the maximal achievable levels during that time.

Maximal multifunctionality was then found by solving the optimization problem:

$$\text{minimize}\ \max\left(\text{loss}_1, \text{loss}_2, \ldots, \text{loss}_k\right)$$

where k is the number of objectives. When multifunctionality was maximized, $k = 6$ after the six objectives described above. When management was planned to target timber production, forest multifunctionality was maximized under the constraint that timber production (harvest income) reached its maximal value:

$$\text{minimize}\ \max\left(\text{loss}_1, \text{loss}_2, \ldots, \text{loss}_k\right)$$

$$\text{subject to} \sum_{i=1}^{n} \text{income}_{i,j} = \max_{\text{tot, income}}$$

where $k = 5$, as timber production is considered separate from multifunctionality, and $\max_{\text{tot,income}}$ is the maximal value of harvest income over the landscape. The maximal value of harvest income was calculated separately for each 20-year planning horizon, always discounting to the start of the planning horizon. The optimization model was created using the Pyomo software (Hart et al. 2012) and solved with the IBM ILOG CPLEX optimizer, version 12.6.2 (https://www.ibm.com/products/ilog-cplex-optimization-studio). As a quantitative measure of multifunctionality (*MF*), we used

$$\text{MF} = 1 - \max\left(\text{loss}_1, \text{loss}_2, \ldots, \text{loss}_k\right)$$

where $\max(\text{loss}_1, \text{loss}_2, \ldots, \text{loss}_k)$ is the value found by the optimization model. This measure directly shows how large a proportion each objective reaches of its potential maximum. For example, if MF = 0.5, each objective reaches at least 50% of its potential maximal level. While other methods for measuring multifunctionality have been proposed (Manning et al. 2018), we chose to use this one as it guarantees a supply of every objective (as opposed to averaging, clustering, or threshold-based methods) and has a straightforward interpretation. We note that our chosen approach assumes that all objectives have equal importance, which may not be the case in real decision-making contexts. However, we argue that it is justified here as explicit information on the relative importance placed on each objective by decision makers or other stakeholders is not available.

Resilience analysis

In order to examine the resilience of forest multifunctionality to intensive forestry, we designed a simulation tree of alternative future scenarios where each node represents a choice between targeting maximal timber production or maximal multifunctionality (Fig. 1). Choices were made for 20 years at a time, representing realistic management planning horizons (Kangas et al. 2015). If forest multifunctionality was targeted in a given planning horizon, it was also targeted in all following horizons. If timber production was targeted in a planning horizon, in the following horizon a choice was again made between timber production and multifunctionality. A change of management focus from timber production to multifunctionality was always followed by 100 years of multifunctionality-focused planning (i.e., five planning horizons). The scenario tree comprised a total of six paths, consisting of consecutive, 20-year planning horizons (Fig. 1).

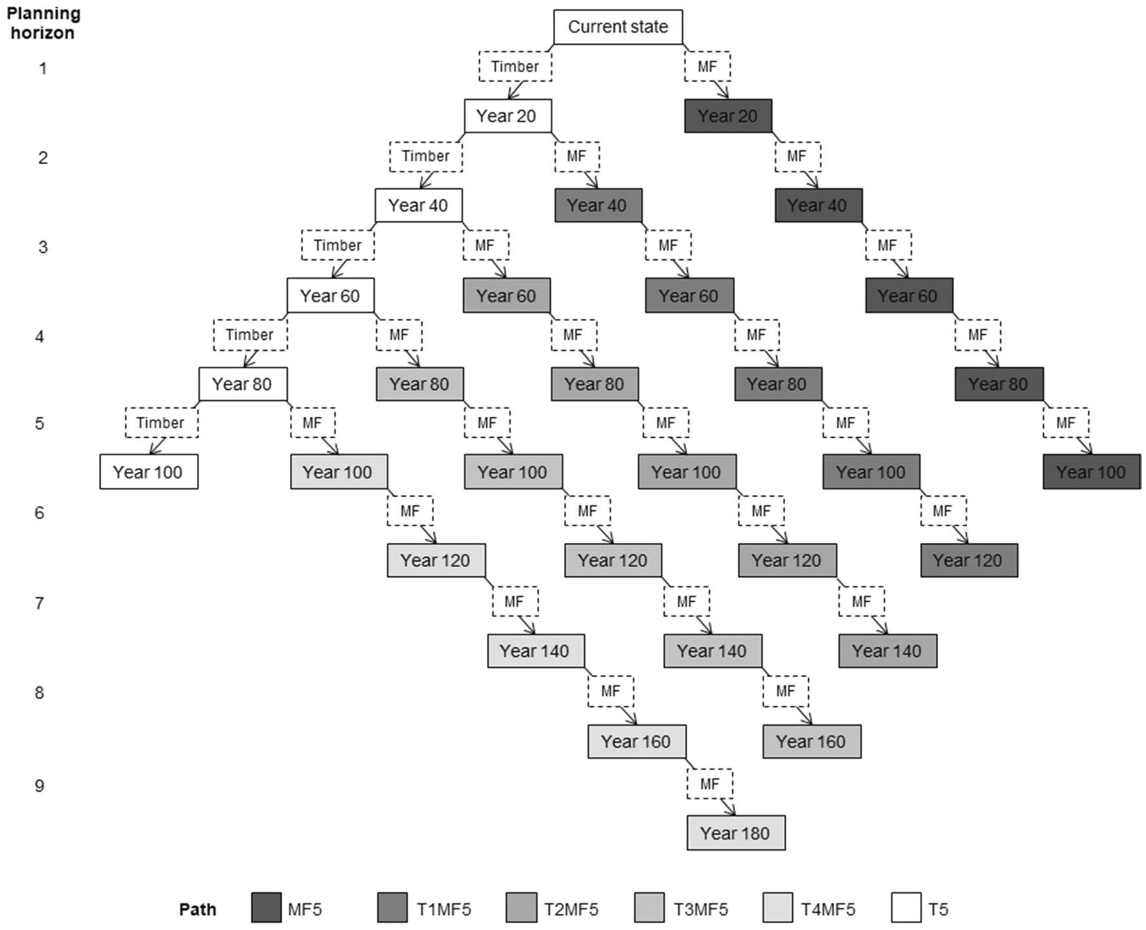

Fig. 1 The scenario tree designed to create alternative future paths for the study forest. Each arrow represents a planning horizon where the development of the forest is simulated for 20 years into the future under a range of alternative management regimes, out of which the set is then identified by multiobjective optimization that maximizes either income from timber harvests ('Timber') or forest multifunctionality ('MF'). If forest multifunctionality is targeted in a given planning horizon, it is also targeted in all following horizons. If timber production is targeted in a planning horizon, in the following horizon a choice is made between timber production and multifunctionality, creating a new branch in the tree. The legend shows the abbreviations used for the six paths

The resistance of forest multifunctionality to intensive forestry was examined by comparing multifunctionality that is achievable under timber-focused management and under multifunctionality-focused management. If timber-focused management provides lower multifunctionality than multifunctionality-focused management, multifunctionality is not resistant to intensive forestry. Similarly, the recovery of multifunctionality was examined by comparing its value between consistently multifunctionality-focused management and multifunctionality-focused management following timber-focused management. If multifunctionality cannot recover after the forest has been used intensively despite a change in management objectives, the system's ability to transform to support multifunctionality has decreased. Besides the value of multifunctionality, we recorded the distributions of the alternative management regimes comprising the optimal management combinations across the study area in each of the planning horizons.

Results

The outcomes of multifunctionality-focused management and timber-focused management differed considerably with the value of multifunctionality being approximately ten times higher under 100 years of multifunctionality-focused management than under 100 years of timber-focused management. When managed consistently for multifunctionality, the study forest's potential for the joint production of all the objectives improved over time across all planning horizons except the last, with multifunctionality reaching at most a value of 0.64 (black dots in Fig. 2a). When management consistently prioritized timber production and

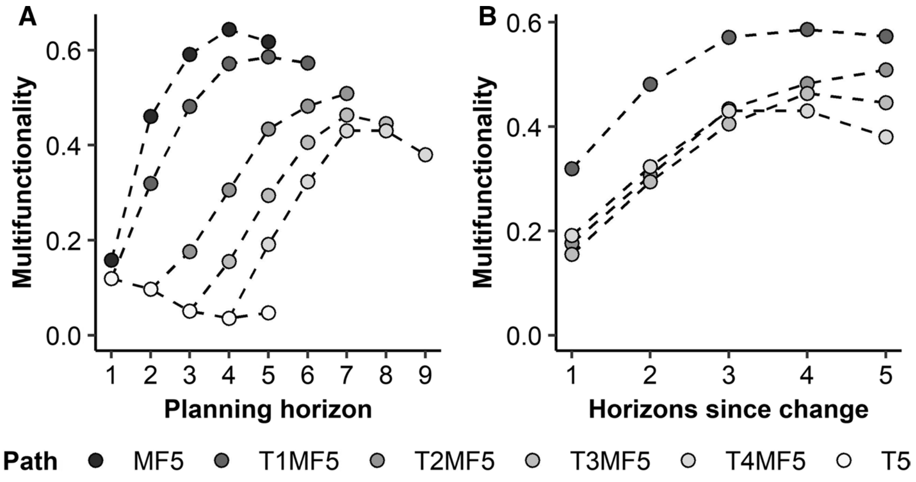

Fig. 2 Forest multifunctionality across time under the alternative management paths. **a** Multifunctionality under all six paths in their entirety. **b** Multifunctionality under the four paths in which the focus of management planning was changed from timber to multifunctionality with the number of planning horizons that have passed since the management change on the x-axis. The dashed lines have been added to connect the points to visualize the progression of the alternative paths

multifunctionality was given secondary importance, forest multifunctionality varied between 0.04 and 0.12 across the planning horizons and decreased over time (white dots in Fig. 2a). The large difference between multifunctionality-focused and timber-focused scenarios indicates that forest multifunctionality was not resistant to intensive forestry.

When the focus of the management planning was switched from timber production to multifunctionality between planning horizons, forest multifunctionality always increased, that is, began to recover. In these scenarios the values of multifunctionality ranged between the extremes of the consistently multifunctionality-focused and timber-focused paths (Fig. 2a). However, multifunctionality did not reach values as high as under consistent multifunctionality-focused management in any of the paths where the forest had been first managed with a timber production focus (Fig. 2a). That is, there was no full recovery of multifunctionality in the timeframe of the study. In almost all the scenarios, multifunctionality again deteriorated near the end of the planning horizon. In addition, if the timber-focused management was continued for more than one planning horizon, the values of multifunctionality achieved in the following multifunctionality-focused planning horizons remained lower than if the management change was preceded by only one timber-focused planning horizon (Fig. 2b). The decrease in the rate of recovery caused by timber-focused management suggests a loss of resilience—specifically, a loss of the system's ability to recover and be transformed into multifunctional forestry.

When management targeted maximal multifunctionality, better outcomes were reached most of the time also in terms of individual objectives than when prioritizing timber production. When multifunctionality was the focus, carbon storage, scenic beauty, and dead wood availability reached higher values than under timber-focused management in every planning horizon (Fig. 3d–f). Following a change of management focus, carbon storage and scenic beauty eventually increased to similar levels as in path MF5 (Fig. 3d–e), whereas dead wood availability did not (Fig. 3f). Bilberry production was higher under multifunctionality-focused than timber-focused management in half of the planning horizons (mainly in paths MF5 and T1MF5), and approximately equal in the rest (Fig. 3b). This indicates that dead wood availability and bilberry production in particular were not resilient to long-term intensive forest management. In contrast, the values of timber production and cowberry production were higher under timber-focused management than under multifunctionality-focused management except for the last planning horizons of paths T3MF5 and T4MF5 (Fig. 3a, c).

An examination of the achievable levels of the six individual objectives under all alternative paths suggests that the value of multifunctionality was mainly limited by either timber production or by dead wood availability. Under consistently multifunctionality-focused management, timber production and dead wood availability reached equal relative levels from the first planning horizon (Fig. 3a, f, Table S1). When timber production was prioritized, dead wood availability was always the objective furthest from its maximal value, i.e., limiting the value of multifunctionality (Table S1). Then again, when management was changed to target multifunctionality, timber production dropped to be the furthest from its maximal value together with slowly increasing dead wood availability (Fig. 3a, f, Table S1). In the last planning horizon of path T2MF5, last two horizons of T3MF5, and last three horizons of T4MF5, that is, after the total simulation time exceeded 140 years, the value of timber production increased considerably and multifunctionality was limited by dead wood availability and bilberry production, equally (Table S1). The values of the rest of the objectives varied between approximately 50 % and 100 % of their maximal levels in all the paths and planning horizons (Table S1).

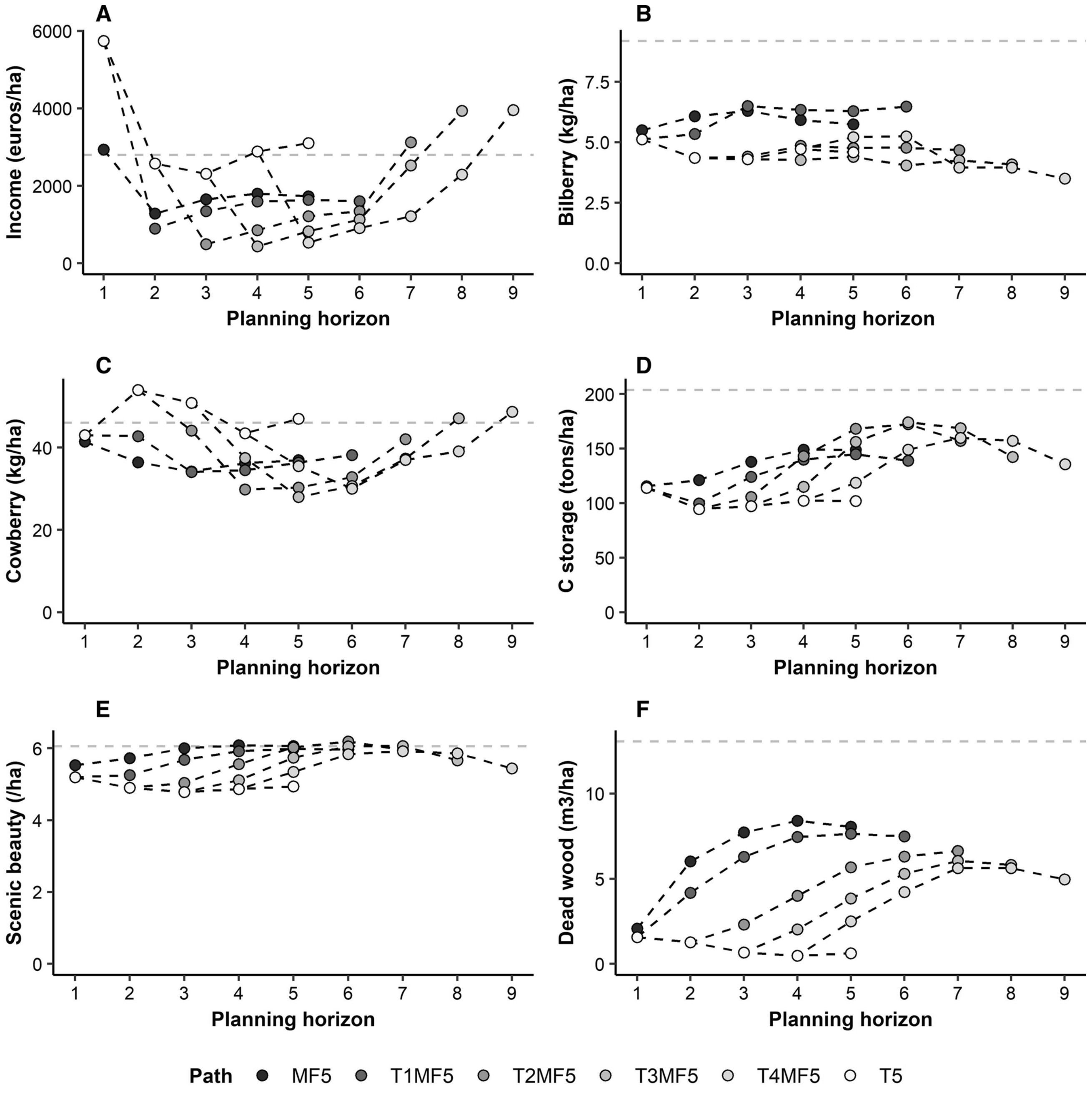

Fig. 3 Values of the six objectives included in the analyses under all management paths and all planning horizons. The dashed lines connect the points in order by time for graphical comparison. The horizontal dashed line shows the reference value for each objective calculated from single objective optimizations and averaged across a 100-year planning horizon (see "Methods")

Whenever management was planned for maximum multifunctionality, the most commonly used management regime was set-aside (no management or harvesting conducted). Under consistently multifunctionality-focused management, between 54 and 77% of forest area was set-aside (Fig. 4). In the paths where management focus was changed from timber production to multifunctionality, set-aside was at least as common, varying between and 64 and 89% of forest area (Fig. 4). Even when timber production was maximized, part of the area was set-aside and not harvested. Note, however, that the planning horizons were 20 years long and it is possible that no harvesting takes place in a 20-year period also under rotation forestry, where the rotation lengths are typically 70–90 years. In four out of five planning horizons where timber production was maximized, continuous cover forestry was the most widely used regime (36%–52%

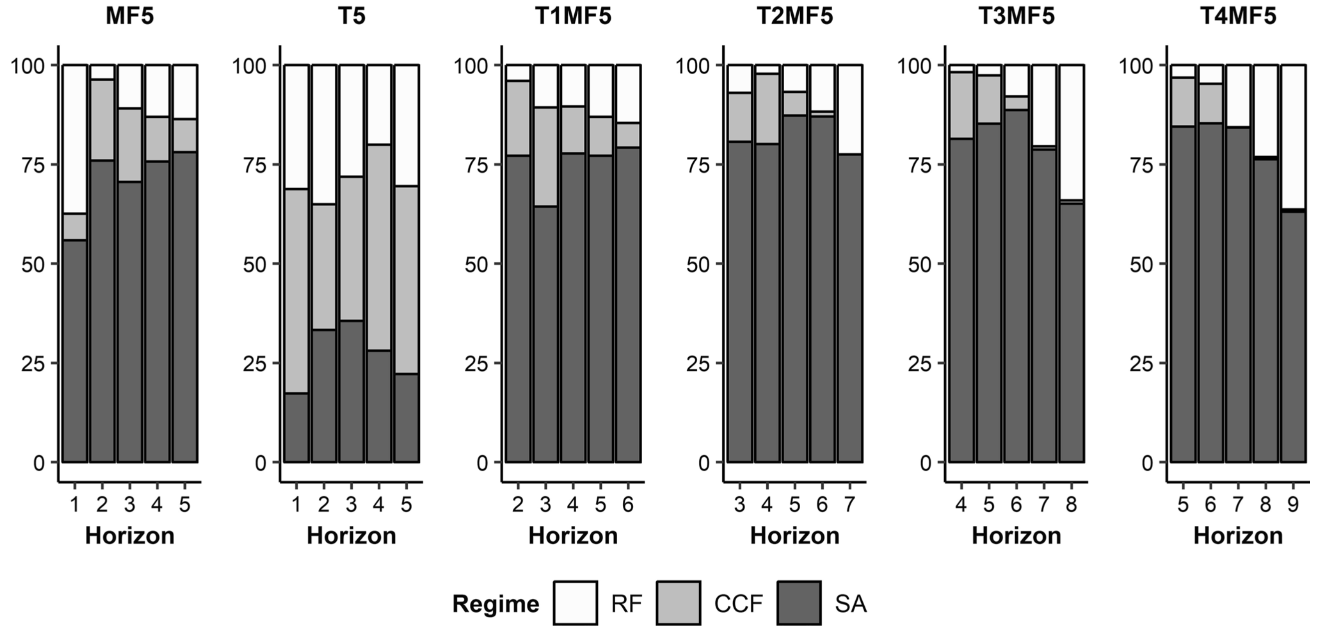

Fig. 4 Distributions of the alternative management regimes in all management paths and all planning horizons. Values on the y-axis show percentage of forest area under the management regime. The first planning horizon of path T1MF5, the first two planning horizons of T2MF5, etc., are the same as of path T5, and therefore not shown. The abbreviations in the legend refer to: RF—rotation forestry, CCF—continuous cover forestry, and SA—set-aside

of forest area; Fig. 4). There were some clear differences between the alternative management regimes in terms of the levels of individual objectives that they provided (Figure S1). In particular, bilberry yields were favored by continuous cover forestry, cowberry yields were highest under rotation forestry, and dead wood availability was highest under set-aside (Figure S1).

Discussion

We demonstrate that intensive forestry is likely to result in losses of multiple non-timber forest benefits, i.e., to reduce forest multifunctionality, as well as in the ability of several benefits to recover after a period of intensive management. The results correspond to different components of resilience: resistance, recovery, and transformation capacity. In our analysis, forest multifunctionality was not resistant to intensive forestry nor could it easily recover from it, and time under intensive forestry exacerbated the negative impacts, indicating decreasing transformation capacity of the system. Our study suggests that the negative impacts of intensive ecosystem management can be long-lasting and even cumulative. In addition, it demonstrates how the concept of resilience and its components can be used together with simulation tools to examine the ability of production landscapes to maintain the provision of diverse benefits under intensive management.

We considered five ecosystem services (timber production, bilberry production, cowberry production, carbon storage, and scenic beauty) and one biodiversity feature (availability of dead wood resources) as forest management objectives and components of forest multifunctionality. When forest management consistently targeted forest multifunctionality, all the objectives could reach up to over 60% of their potential maximums at the same time. Under timber-focused management, the corresponding number was 4–12%. The clearly lower multifunctionality under timber-focused management than under multifunctionality-focused management shows that in our framework multifunctionality is not resistant to intensive forestry. In the scenarios where management focus was changed from timber to multifunctionality, multifunctionality increased in time after the change, indicating that it may recover to some extent. However, it always remained lower than in the reference scenario of constant multifunctionality targeting. The result that multifunctionality was and remained lower the longer the forest had been managed with a timber production focus indicates a loss of resilience that became increasingly consequential as intensive forestry was continued, i.e., a growing recovery debt (Moreno-Mateos et al. 2017). The management options enabled by the regimes included in our simulations were not sufficient to effectively reverse the impacts of timber-focused forestry. Although the specific management history of the study area is not known, the decreasing multifunctionality under the consistently timber-focused scenario and the growing recovery debt suggest that past management has not been as intensive as in the simulated timber-focused scenario. Thus, in our framework, intensive forestry appears to make the transition to other forest management systems with other goals more difficult. This could be problematic under, for example, climate change or other new natural or social conditions (Messier et al. 2015). The ability of forest biodiversity to recover from intensive exploitation has been studied in restoration experiments (Halme et al. 2013), and several earlier studies have shown the negative impacts of intensive forestry on other forest ecosystem services than timber production (Pohjanmies et al. 2017b; Nolet et al. 2018; Jonsson et al. 2020), but this is to our knowledge the first study examining the ability of forest multifunctionality to recover from intensive forestry.

The value of multifunctionality was mostly limited by dead wood availability or timber production. Under timber-focused management, dead wood availability was consistently very low, while under multifunctionality-focused management dead wood availability and timber production were at equal levels (relative to their respective potential maximal values). A change in management focus from timber to multifunctionality led to a sharp decline in income from timber production and an increase in dead wood availability. In other words, the achievable multifunctionality was bound by the trade-off between these two objectives. However, also bilberry production and carbon storage showed substantial decreases under timber-focused management. We must note though that as we did not consider carbon stored in harvested timber, the negative impact of harvesting on carbon storage may be overestimated, depending on the final use and lifespan of the harvested wood. The levels for bilberry production, carbon storage, and scenic beauty were lower in the timber production scenario, but cowberry production, which has been found to be easier to reconcile with forestry (Peura et al. 2016), was not. A tentative conclusion to draw from these patterns is that forest management interventions have higher potential to hurt conservation objectives than ecosystem services, as suggested by, for example, Roberge et al. (2016).

In almost all the scenarios, multifunctionality decreased near the end of the planning horizon, including in the scenario where maximal multifunctionality was consistently targeted. Two potential interpretations can be made from this. First, it may mean that there is a maximal peak level that multifunctionality can reach, after which it will inevitably decrease at least for a time. A second, and related, interpretation is that the multifunctionality of a system like a forest landscape will fluctuate because the system is changing; in this case, the forest is undergoing succession (natural and/or influenced by present and previous management) (Kuuluvainen and Gauthier 2018). It may therefore be challenging to maintain a stable level of forest multifunctionality even when multifunctionality is explicitly targeted. Nevertheless, our results highlight that the most dramatic declines in multifunctionality are caused by intensive forest harvesting.

In terms of the management regimes applied in the alternative scenarios, our results show a great importance for leaving forests unharvested in promoting forest multifunctionality. When maximizing multifunctionality, set-aside was by far the most widely applied regime, ranging from 54 to 89% of total forest area, with the remaining area under rotation or continuous cover forestry. This suggests that at least temporary protection is required to enhance forest multifunctionality, whereas modifications to silvicultural practices (for example, extended rotations or continuous cover forestry) alone do not suffice. This conclusion is supported by earlier findings about stand-level trade-offs between timber harvesting and other forest management objectives and the ensuing difficulty of improving multifunctionality by active management as compared with protection (Gamfeldt et al. 2013; Pohjanmies et al. 2017b; Strengbom et al. 2017). This seems to contradict suggestions that continuous cover forestry in particular could be important in multifunctional forestry (Laiho et al. 2011; Pukkala 2016; Peura et al. 2018). However, continuous cover forestry was favored more than rotation forestry in the planning horizons where income from timber production was given priority also in our study. Our results therefore support the view that continuous cover forestry can support multifunctionality better than rotation forestry when extensive forest protection is not possible. We note, then again, that the management alternatives simulated in our study were limited in terms of all of the choices that can be made in stand management, such as the timing and intensity of harvesting, use of fertilization, and choice of tree species planted after final felling or favored during thinnings. For example, as encouraged by Finnish recommendations and as implemented in our study, rotation forestry favors the development of coniferous monocultures, but research suggests that mixed-species stands may be better at providing multiple ecosystem services (Huuskonen et al. 2021). Tree species choice may also be guided by specific management goals such as resistance to herbivory instead of site type, with consequences on ecosystem services and biodiversity (Felton et al. 2020).

In this study, we examined the resilience of forest multifunctionality to management disturbances caused by intensive forestry. Besides intensifying resource use, production landscapes are faced with uncertainties caused by climate change, fires, pests, pollution, and loss of biodiversity, which also raise concerns over the long-term maintenance of ecosystem services, resilience to natural disturbances, and the stability of resource production itself (Millar et al. 2007; Lindner et al. 2010; Isbell et al. 2015; Seidl et al. 2016). In particular, regulating services interact with other types of ecosystem services, and maintaining the former may increase the stability of the latter (Bennett et al. 2009). In this study, several regulating services (for example, water regulation, maintenance of soil fertility, or pest control) were not considered due to lack of suitable methods and indicators; however, they may also be affected by forestry activities (Pohjanmies et al. 2017a) and it would be important to understand and ensure their long-term maintenance. The resilience of the forest was analyzed only in terms of the response of forest multifunctionality to intensive forest exploitation and not, for example, to natural disturbances. As modeling methods develop, natural disturbances at varying intensities can be included in the forest growth simulations and the framework can be used to explore the responses of the system under the influence of both natural and anthropogenic pressures. This would add further depth to the analysis and perhaps more realistically reflect a future of growing uncertainties (Bennet and Balvanera 2007; Millar et al. 2007; Oliver et al. 2015). Also in this context the implications of tree species choice may be especially meaningful (Felton et al. 2016).

Following the above considerations, we must note that our study is limited by the availability of methods to describe the complex dynamics of forest ecosystems and their ecosystem service-producing processes. Because of the large spatial and temporal scales required to describe forest dynamics, analyses such as the current study must rely on limited input data and modeling tools to make predictions. As noted above, our study included only some of the ecosystem services provided by forests, as well as only one indicator of forest biodiversity. The set of objectives included in the multifunctionality measure, the weights given to them, and the parameter sensitivity of the models used to estimate them unavoidably influence both the predicted value of multifunctionality and the set of management actions found to maximize it. The choice of the multifunctionality measure itself also affects the results and conclusions (Manning et al. 2018). For example, using a threshold approach, where multifunctionality is measured as the number of objectives achieving a set level of their maximal values, could produce smaller differences between the scenarios than found in our study. In addition, we were not able to account for the impacts of climate change or other future conditions in our projections. Finally, the set of simulated management alternatives also limits the solution space available in the optimization and thereby the possibility to reconcile multiple objectives, as discussed above. Alternatives that differ from current recommendations more drastically than as implemented in our study, e.g., in terms of tree species choice, could produce different results, but, then again, would also increase the uncertainty of the forest growth and ecosystem service models. That said, previous findings about the conflicts between forest harvesting, multifunctionality, and conservation support our interpretations.

Overall, our results caution that intensive forestry not only can reduce the supply of non-timber benefits from forests but can also hinder the transformation to more multifunctional forest landscapes once intensive forestry is ceased, for example, for reasons of climate or social policies. Ecosystem management for landscape multifunctionality entails a change of management focus from intensive exploitation to a more diverse set of approaches (Fischer et al. 2006). Our results suggest that if high forest multifunctionality is desired, such a change should not be delayed in view of the uncertainty of future goals for forestry and forest land. Forest management in boreal regions is marked by a widespread use of even-aged rotation forestry and resistance to take up alternative management systems, arguably described as a 'lock-in' to the even-aged paradigm (Moen et al. 2014; Jonsson et al. 2019). Because of the long timeframes with which forests develop and respond to management activities, so-called lock-ins in forest management are difficult to reverse and thus are particularly risky. Such 'lock-ins' in forest management should be further studied with more alternative management options and with a multidisciplinary perspective to identify all the mechanisms maintaining them (Holling and Meffe 1996). The uncertainties related to future climatic, ecological, and socioeconomic conditions make it of great importance to understand and promote the resilience of these ecosystems (Chapin et al. 2007; Reyer et al. 2015). For examinations of future delivery of ecosystem services under different conditions and in different regions, our approach of using step-wise simulation and management optimization should be developed further and repeated in different areas and with different input data in order to validate our conclusions and to improve the understanding of landscape multifunctionality and resilience. We conclude that benefits from the multitude of provisioning, regulating, and cultural services ought to be considered in management planning already now in order to secure their supply also in the future. Doing so would likely have large implications not only for boreal forestry but for the management of all production landscapes used for forestry or agriculture and other intensively human-dominated areas.

Author contributions TP designed the study; TP and KE performed the research; KE contributed new models; TP analyzed the data and led the writing of the manuscript; all authors interpreted the results and participated in writing the paper.

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Data availability The data used in this study are owned and archived by the Finnish Forest Centre (www.metsakeskus.fi). The data are available from the authors upon reasonable request and with permission of the Finnish Forest Centre.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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References

Äijälä O, Koistinen A, Sved J et al. (Eds.) (2014) Hyvän metsänhoidon suositukset - Metsänhoito. Metsätalouden kehittämiskeskus Tapio

Başkent EZ, Keleş S, Kadıoğulları Aİ, Bingöl Ö (2011) Quantifying the effects of forest management strategies on the production of forest values: timber, carbon, oxygen, water, and soil. Environ Model Assess 16:145–152. https://doi.org/10.1007/s10666-010-9238-y

Bennet EM, Balvanera P (2007) The future of production systems in a globalized world. Front Ecol Environ 5:191–198. https://doi.org/10.1890/1540-9295(2007)5[191:TFOPSI]2.0.CO;2

Bennett EM, Peterson GD, Gordon LJ (2009) Understanding relationships among multiple ecosystem services. Ecol Lett 12:1394–404. https://doi.org/10.1111/j.1461-0248.2009.01387.x

Biggs R, Schlüter M, Biggs D et al (2012) Toward principles for enhancing the resilience of ecosystem services. Annu Rev Environ Resour 37:421–448. https://doi.org/10.1146/annurev-environ-051211-123836

Brockerhoff EG, Barbaro L, Castagneyrol B et al (2017) Forest biodiversity, ecosystem functioning and the provision of ecosystem services. Biodivers Conserv 26:3005–3035. https://doi.org/10.1007/s10531-017-1453-2

Chapin FS, Danell K, Elmqvist T et al (2007) Managing climate change impacts to enhance the resilience and sustainability of Fennoscandian forests. Ambio 36:528–33. https://doi.org/10.1579/0044-7447

Cumming GS, Olsson P, Chapin FS, Holling CS (2013) Resilience, experimentation, and scale mismatches in social-ecological landscapes. Landsc Ecol 28:1139–1150. https://doi.org/10.1007/s10980-012-9725-4

Edwards DP, Tobias JA, Sheil D et al (2014) Maintaining ecosystem function and services in logged tropical forests. Trends Ecol Evol 29:511–520. https://doi.org/10.1016/j.tree.2014.07.003

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

Felton A, Gustafsson L, Roberge JM et al (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

Felton A, Petersson L, Nilsson O et al (2020) The tree species matters: biodiversity and ecosystem service implications of replacing Scots pine production stands with Norway spruce. Ambio 49:1035–1049. https://doi.org/10.1007/s13280-019-01259-x

Fischer J, Lindenmayer DB, Manning AD (2006) Biodiversity, ecosystem function, and resilience: ten guiding principles for commodity production landscapes. Front Ecol Environ 4:80–86. https://doi.org/10.1890/1540-9295(2006)004[0080:BEFART]2.0.CO;2

Foley JA (2005) Global consequences of land use. Science 80(309):570–574. https://doi.org/10.1126/science.1111772

Folke C, Carpenter S, Walker B et al (2004) regime shifts, resilience, and biodiversity in ecosystem management. Annu Rev Ecol Evol Syst 35:557–581. https://doi.org/10.1146/annurev.ecolsys.35.021103.105711

Gamfeldt L, Snäll T, Bagchi R et al (2013) Higher levels of multiple ecosystem services are found in forests with more tree species. Nat Commun 4:1340. https://doi.org/10.1038/ncomms2328

Gao T, Nielsen AB, Hedblom M (2015) Reviewing the strength of evidence of biodiversity indicators for forest ecosystems in Europe. Ecol Indic 57:420–434. https://doi.org/10.1016/j.ecolind.2015.05.028

Gauthier S, Bernier P, Kuuluvainen T et al (2015) Boreal forest health and global change. Science 80(349):819–822. https://doi.org/10.1126/science.aaa9092

Ghazoul J, Chazdon R (2017) Degradation and recovery in changing forest landscapes: a multiscale conceptual framework. Annu Rev Environ Resour 42:161–188. https://doi.org/10.1146/annurev-environ-102016-060736

Gundersen VS, Frivold LH (2008) Public preferences for forest structures: a review of quantitative surveys from Finland, Norway and Sweden. Urban For Urban Green 7:241–258. https://doi.org/10.1016/j.ufug.2008.05.001

Halme P, Allen KA, Auniņš A et al (2013) Challenges of ecological restoration: lessons from forests in northern Europe. Biol Conserv 167:248–256. https://doi.org/10.1016/j.biocon.2013.08.029

Hart WE, Laird C, Watson J-P, Woodruff DL (2012) Pyomo - optimization modeling in python. Springer, NewYork

Holling CS, Meffe GK (1996) Command and control and the pathology of natural resource management. Conserv Biol 10:328–337. https://doi.org/10.1046/j.1523-1739.1996.10020328.x

Huuskonen S, Domisch T, Finér L et al (2021) What is the potential for replacing monocultures with mixed-species stands to enhance ecosystem services in boreal forests in Fennoscandia? For Ecol Manage 479:118558. https://doi.org/10.1016/j.foreco.2020.118558

Isbell F, Tilman D, Polasky S, Loreau M (2015) The biodiversity-dependent ecosystem service debt. Ecol Lett 18:119–134. https://doi.org/10.1111/ele.12393

Jonsson M, Bengtsson J, Gamfeldt L et al (2019) Levels of forest ecosystem services depend on specific mixtures of commercial tree species. Nat Plants 5:141–147. https://doi.org/10.1038/s41477-018-0346-z

Jonsson M, Bengtsson J, Moen J et al (2020) Stand age and climate influence forest ecosystem service delivery and multifunctionality. Environ Res Lett 15:0940a8. https://doi.org/10.1088/1748-9326/abaf1c

Kangas A, Kurttila M, Hujala T et al (2015) Decision support for forest management. Springer International Publishing, Cham

Kareiva P, Watts S, McDonald R, Boucher T (2007) Domesticated nature: shaping landscapes and ecosystems for human welfare. Science 316:1866–1869. https://doi.org/10.1126/science.1140170

Kuuluvainen T, Gauthier S (2018) Young and old forest in the boreal: critical stages of ecosystem dynamics and management under global change. For Ecosyst 5:26. https://doi.org/10.1186/s40663-018-0142-2

Kuuluvainen J, Karppinen H, Ovaskainen V (1996) Landowner objectives and nonindustrial private timber supply. For Sci 42:300–309

Laiho O, Lahde E, Pukkala T (2011) Uneven- vs even-aged management in Finnish boreal forests. Forestry 84:547–556. https://doi.org/10.1093/forestry/cpr032

Lindner M, Maroschek M, Netherer S et al (2010) Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. For Ecol Manage 259:698–709. https://doi.org/10.1016/j.foreco.2009.09.023

Liski J, Palosuo T, Peltoniemi M, Sievänen R (2005) Carbon and decomposition model Yasso for forest soils. Ecol Modell 189:168–182. https://doi.org/10.1016/j.ecolmodel.2005.03.005

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. https://doi.org/10.1890/1051-0761(2006)016[1865:PTDOSP]2.0.CO;2

Manning P, van der Plas F, Soliveres S et al (2018) Redefining ecosystem multifunctionality. Nat Ecol Evol 2:427–436. https://doi.org/10.1038/s41559-017-0461-7

Mazziotta A, Podkopaev D, Triviño M et al (2017) Quantifying and resolving conservation conflicts in forest landscapes via multiobjective optimization. Silva Fenn 51:1–19. https://doi.org/10.14214/sf.1778

Messier C, Puettmann K, Chazdon R et al (2015) From management to stewardship: viewing forests as complex adaptive systems in an uncertain world. Conserv Lett 8:368–377. https://doi.org/10.1111/conl.12156

Miina J, Hotanen J, Salo K (2009) Modelling the abundance and temporal variation in the production of bilberry (Vaccinium myrtillus L.) in Finnish mineral soil forests. Silva Fenn 43:577–593. https://doi.org/10.14214/sf.181

Millar CI, Stephenson NL, Stephens SL (2007) Climate change and forests of the future: managing in the face of uncertainty. Ecol Appl 17:2145–2151. https://doi.org/10.1890/06-1715.1

Moen J, Rist L, Bishop K et al (2014) Eye on the Taiga: removing global policy impediments to safeguard the boreal forest. Conserv Lett 7:408–418. https://doi.org/10.1111/conl.12098

Moreno-Mateos D, Barbier EB, Jones PC et al (2017) Anthropogenic ecosystem disturbance and the recovery debt. Nat Commun 8:14163. https://doi.org/10.1038/ncomms14163

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 et al (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

Oliver TH, Heard MS, Isaac NJB et al (2015) Biodiversity and resilience of ecosystem functions. Trends Ecol Evol 30:673–684. https://doi.org/10.1016/j.tree.2015.08.009

Oliver TH, Boyd E, Balcombe K et al (2018) Overcoming undesirable resilience in the global food system. Glob Sustain 1:1–9. https://doi.org/10.1017/sus.2018.9

Pan Y, Birdsey RA, Fang J et al (2011) A large and persistent carbon sink in the world's forests. Science 333:988–993. https://doi.org/10.1126/science.1201609

Peltola A (ed) (2014) Finnish statistical yearbook of forestry. Finnish Forest Research Institute, Joensuu

Peterson G (2000) Political ecology and ecological resilience: an integration of human and ecological dynamics. Ecol Econ 35:323–336. https://doi.org/10.1016/S0921-8009(00)00217-2

Peura M, Triviño M, Mazziotta A et al (2016) Managing boreal forests for the simultaneous production of collectable goods and timber revenues. Silva Fenn 50:1–17. https://doi.org/10.14214/sf.1672

Peura M, Burgas D, Eyvindson K et al (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, Triviño M, Le Tortorec E et al (2017) Impacts of forestry on boreal forests: an ecosystem services perspective. Ambio 46:743–755. https://doi.org/10.1007/s13280-017-0919-5

Pohjanmies T, Triviño M, Le Tortorec E et al (2017) Conflicting objectives in production forests pose a challenge for forest management. Ecosyst Serv. https://doi.org/10.1016/j.ecoser.2017.06.018

Pukkala T (2016) Which type of forest management provides most ecosystem services? For Ecosyst 3:9. https://doi.org/10.1186/s40663-016-0068-5

Pukkala T, Kellomaki S, Mustonen E (1988) Prediction of the amenity of a tree stand. Scand J For Res 3:533–544. https://doi.org/10.1080/02827588809382538

Pukkala T, Lähde E, Laiho O (2012) Continuous cover forestry in Finland–recent research results. In: Pukkala T, von Gadow K (eds) Continuous cover forestry. Springer, Netherlands, pp 85–128

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

Rassi P, Hyvärinen E, Juslén A, Mannerkoski I (eds) (2010) The 2010 Red list of Finnish species. Ympäristöministeriö & Suomen ympäristökeskus, Helsinki

Reyer CPO, Rammig A, Brouwers N, Langerwisch F (2015) Forest resilience, tipping points and global change processes. J Ecol 103:1–4. https://doi.org/10.1111/1365-2745.12342

Roberge JM, Laudon H, Björkman C et al (2016) Socio-ecological implications of modifying rotation lengths in forestry. Ambio 45:109–123. https://doi.org/10.1007/s13280-015-0747-4

Sánchez-Pinillos M, Leduc A, Ameztegui A et al (2019) Resistance, resilience or change: post-disturbance dynamics of boreal forests after insect outbreaks. Ecosystems. https://doi.org/10.1007/s10021-019-00378-6

Schwenk WS, Donovan TM, Keeton WS, Nunery JS (2012) Carbon storage, timber production, and biodiversity: comparing ecosystem services with multi-criteria decision analysis. Ecol Appl 22:1612–1627. https://doi.org/10.1890/11-0864.1

Seidl R, Spies TA, Peterson DL et al (2016) Searching for resilience: addressing the impacts of changing disturbance regimes on forest ecosystem services. J Appl Ecol 53:120–129. https://doi.org/10.1111/1365-2664.12511

Silvennoinen H, Alho J, Kolehmainen O, Pukkala T (2001) Prediction models of landscape preferences at the forest stand level. Landsc Urban Plan 56:11–20. https://doi.org/10.1016/S0169-2046(01)00163-3

Strengbom J, Axelsson EP, Lundmark T, Nordin A (2017) Trade-offs in the multi-use potential of managed boreal forests. J Appl Ecol. https://doi.org/10.1111/1365-2664.13019

Thompson ID, Okabe K, Tylianakis JM et al (2011) Forest biodiversity and the delivery of ecosystem goods and services: translating science into policy. Bioscience 61:972–981. https://doi.org/10.1525/bio.2011.61.12.7

Tikkanen O-P, Martikainen P, Hyvarinen E et al (2006) Red-listed boreal forest species of Finland: associations with forest structure, tree species, and decaying wood. Ann Zool Fennici 43:373–383

Triviño M, Pohjanmies T, Mazziotta A et al (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, Thum T, Järvinen H et al (2009) Leaf litter decomposition—Estimates of global variability based on Yasso07 model. Ecol Modell 220:3362–3371. https://doi.org/10.1016/j.ecolmodel.2009.05.016

Tuomi M, Laiho R, Repo A, Liski J (2011) Wood decomposition model for boreal forests. Ecol Modell 222:709–718. https://doi.org/10.1016/j.ecolmodel.2010.10.025

Turtiainen M, Miina J, Salo K, Hotanen J (2013) Empirical prediction models for the coverage and yields of cowberry in Finland. Silva Fenn. https://doi.org/10.14214/sf.1005

Vaara M, Saastamoinen O, Turtiainen M (2013) Changes in wild berry picking in Finland between 1997 and 2011. Scand J For Res 28:586–595. https://doi.org/10.1080/02827581.2013.786123

Walker B, Salt D (2006) Resilience thinking: sustaining ecosystems and people in a changing world. Island Press, Washington

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