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Multi-objective forestry increases the production of ecosystem services

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Boreal forests produce multiple ecosystem services for the society. Their trade-offs determine whether they should be produced simultaneously or whether it is preferable to assign separate areas to different ecosystem services. We use simulation and optimization to analyse the correlations, trade-offs and production levels of several ecosystem services in single- and multi-objective forestry over 100 years in a boreal forest landscape. The case study area covers 3600 ha of boreal forest, consisting of 3365 stands. The ecosystem services and their indicators (in parentheses) considered are carbon sequestration (forestry carbon balance), biodiversity (amount of deadwood and broadleaf volume), economic profitability of forestry (net present value of timber production) and timber supply to forest industry (volume of harvested timber). The treatment alternatives simulated for each of the stands include both even-aged rotation forestry (thinning from above with clear cut) and continuous cover forestry regimes (thinning from above with no clear cut). First, we develop 200 Pareto optimal plans by maximizing multi-attribute utility functions using random weights for the ecosystem service indicators. Second, we compare the average level of ecosystem services in single- and multi-objective forestry. Based on our findings, forestry carbon balance and the amount of deadwood correlate positively with each other, and both of them correlate negatively with harvested timber volume and economic profitability of forestry. Despite this, the simultaneous maximization of multiple objectives increased the overall production levels of several ecosystem services, which suggests that the management of boreal forests should be multi-objective to sustain the simultaneous provision of timber and other ecosystem services.

Introduction

Boreal forests provide multiple ecosystem services for the society, ranging from the provisioning of timber and non-wood products to regulating functions (e.g. carbon sequestration and maintenance of biodiversity) and cultural services (e.g. recreational environments) (Spence, 2001; Reid *et al.,* 2005; Burton *et al.,* 2010; Pan *et al.,* 2011). Boreal forests contribute to climate change mitigation by sequestering carbon from the atmosphere and storing it both in forests and wood-based products. Boreal forests are also important for biodiversity because they provide habitats for numerous species, many of which depend on deadwood (Tikkanen *et al.,* 2007). However, the sustainable joint production of different ecosystem services in boreal forests is challenging due to increasing production targets and the fact that many services compete with each other (Reid *et al.,* 2005; Cardinale *et al.,* 2012). Furthermore, climate change and the associated intensification of disturbance regimes complicate the prediction of future levels of ecosystem services (Temperli *et al.,* 2012; Gauthier *et al.,* 2015; Reyer *et al.,* 2017).

The selected forest management strategy affects the production levels of ecosystem services (i.e. Triviño *et al.,* 2015; Díaz-Yáñez *et al.,* 2019). In recent decades, even-aged rotation forestry has been the prevailing management system in Finland, primarily aiming at high yields of harvested timber, often at the cost of other ecosystem services (Äijälä *et al.,* 2014). This management system has resulted in conifer-dominated forest landscapes with homogeneous stand structures. The use of more variable management strategies, such as continuous cover forestry or combinations of different silvicultural systems, might increase the overall production levels of ecosystem services in boreal forests (Díaz-Yáñez *et al.,* 2019).

A better understanding of the relationships between ecosystem services and their trade-offs would help to optimize forest production and contribute to sustainable management, considering all ecosystem services that are important to the society (Bennett *et al.,* 2009). In boreal forests, trade-offs between the amount of harvested timber and other ecosystem services, such as carbon sequestration, biodiversity and non-wood forest products, are common (Pohjanmies *et al.,* 2017b; Kurttila *et al.,* 2018).

More diverse management at the landscape level could help to decrease the adverse effect of timber harvesting on other ecosystem services (Triviño *et al.,* 2015; Pohjanmies *et al.,* 2017a).

Maximizing an ecosystem service under different minimum amounts of other services maps the Pareto frontier (Borges *et al.,* 2014). For a pair of ecosystem services, this can be graphically represented as a production possibility curve. The slope of the production possibility curve represents the rate at which one ecosystem service must be given up when increasing the amount of the other service. A concave curve indicates an increasing rate of transformation, where the production of near-maximal levels of one service may result in very high losses in the other service. On the other hand, the concave shape also means that at certain levels of one ecosystem service, a small sacrifice in its production may result in a high gain for the production of other services.

Quantifying the trade-offs between different ecosystem services is the key to maximizing the sustainable production of multiple ecosystem services. While many studies have investigated the trade-offs between timber production and individual other services (e.g. Triviño *et al.,* 2015; Luyssaert *et al.,* 2018), this issue has rarely been analysed in a truly multifunctional context with several to many involved ecosystem services. Previous studies have shown that such trade-off curves are often concave (Kangas and Pukkala, 1996; Pukkala, 2002, 2014). One reason for this outcome is decreasing marginal productivity, where each added unit of a production factor increases production by a smaller amount than the previous unit. In addition, each decreased unit of a certain ecosystem service increases the production of the other ecosystem service less and less. Consequently, it may be worthwhile to produce several ecosystem services simultaneously in the same forest landscape (block) rather than assign different forest blocks for different services.

Evaluation of forest multifunctionality requires information on how the supply potential of different ecosystem services is distributed in the forest landscape. Optimal management implies that the varying production potentials of different forest stands are taken into account. Previous studies have analysed the production level of different ecosystem services in a multifunctional setting by using different methodological approaches. One approach is a pre-defined value-based analysis where the preferences for certain ecosystem services are subjective, for example, based on certain stakeholders perspectives (Eskelinen and Miettinen, 2012; Seidl and Lexer, 2013; Langner *et al.,* 2017). This strategy provides the optimal management for a discrete number of preferences that are defined before the analysis. Another alternative is to maximize one of the ecosystem services and find the management strategies that would produce the highest levels for the other ecosystem services (Díaz-Yáñez *et al.,* 2019). As the future needs of societies from forests are hard to define, forest managers would benefit from having a broader understanding on the correlations and trade-offs of the production levels of several ecosystem services. This would help to find compromise management schemes, which will be satisfactory under any future preferences of the society.

We aimed to examine the trade-offs and correlations between several ecosystem services as well as their production levels in single- and multi-objective forestry. To analyse the effect of multi-objective management on ecosystem services, we used an innovative approach based on random objective functions, numerical optimization and Gini index as a measure of multifunctionality. The method randomly varied the weights of different ecosystem services and selected the optimal forest management for each objective function. The degree to which the objective functions were multi-objective was measured with the Gini index. The Gini index was also used to categorize the plans as single- or multi-objective. By using this approach, we were able to express the overall production level of ecosystem services as a function of the degree of multi-objectivity. Based on the assumption of decreasing marginal productivity, we hypothesized that multi-objective management would produce higher average amounts of ecosystem services, compared with single-objective forestry.

The ecosystem services considered were each measured by one or two numerical indicators (in parentheses): carbon sequestration (forestry carbon balance), biodiversity (amount of deadwood and broadleaf volume), economic profitability of forestry (net present value, NPV) and timber supply to forest industry (volume of harvested timber). We used simulation and optimization to analyse the maximal production levels of different ecosystem services and their trade-offs in a boreal forest landscape over a planning period of 100 years.

Methods

Study area and data

The study area of 3600 ha is located in a boreal forest landscape in eastern Finland (62°31′N, 29°23′E) and contains a total of 3365 stands. The stand data are publicly available (Finnish Forest Centre, 2018), and most of the stand attributes have been predicted by remote sensing. In the past, the area has been managed mainly following even-aged rotation forestry (Äijälä *et al.,* 2014). The stands are dominated by Norway spruce, Scots pine and birch spp., and to a lesser extent by other broadleaf species, such as aspen, alder and rowan. Forests cover 84 per cent of the study area. More details and data on the study area can be found in Díaz-Yáñez *et al.* (2019).

Simulation

The compilation of management plans for the case study forest consisted of two steps. First, alternative treatment schedules were simulated for each stand of the forest. Second, the optimal combination of the simulated treatment schedules was found by using combinatorial optimization.

The development of each stand under alternative cutting schedules was simulated for 100 years, using the simulation-optimization software Monsu (Pukkala, 2004). Diameter increment, tree mortality and the amount of advance regeneration (ingrowth) were predicted using the models of Pukkala *et al.* (2013). These models can be used to simulate both rotation forestry and continuous cover forestry. The diameter increments, as predicted by the model, were calibrated as explained in Heinonen *et al.* (2017), to correspond to the diameter increment in the 11th National Forest Inventory of Finland. The initial tree height was calculated using the height models available in Siipilehto (2006) and the height increment during the simulation was calculated based on tree diameter using the models of

Pukkala *et al.* (2009). We assumed a mild climate change—the RCP2.6 forcing scenario, where the mean annual temperature increases by 2°C, annual precipitation by 6 per cent and the atmospheric carbon dioxide (CO_2) concentration to 430 ppm by 2100 (Ruosteenoja *et al.,* 2016). The model that was used to simulate the effect of climate change on tree growth is explained in Seppälä *et al.* (2019). The model gives a growth multiplier for each year, which represents the predicted effect of a changing climate on tree growth.

The treatment schedules simulated for each stand included both rotation forestry and continuous cover forestry alternatives. Rotation forestry included natural or artificial regeneration (seeding, or planting of seedlings), tending treatments for young stands, commercial thinning from above and final felling by clear cut or seed tree cut. In continuous-cover forestry, thinning was simulated from above, and clear cut and artificial regeneration were not used. Instead, advance regeneration and ingrowth were promoted by selective tree cutting. On average, 154 different treatment schedules were simulated per stand. Alternatives were obtained by changing the timing and intensity of the cuttings (see Díaz-Yáñez *et al.,* 2019 for details). A no-cutting schedule was also simulated for every stand.

The mean harvest volume was estimated for the following assortments: sawlog, small log (only for conifers) and pulpwood, using the stem taper functions of Laasasenaho (1982). The assortment volumes were used to calculate the income from timber sales. Economic profitability was measured by summing the discounted values of the management costs and timber sale incomes of the 100-year simulation period and adding the predicted NPV of the final growing stock to the sum of the discounted costs and incomes. A 2 per cent discount rate was used in the calculations. Silvicultural costs and roadside timber prices were the same as in Heinonen *et al.* (2018). Harvesting costs were estimated based on time consumption functions of Rummukainen *et al.* (1995) and the hourly costs of harvester (95€ h^{-1}) and forwarder systems (65€ h^{-1}).

The forestry carbon balance was estimated for the entire study period as the difference between the sequestered and released carbon in several pools, including the carbon emitted during timber harvesting, transport and product manufacturing (Pukkala, 2014), and the substitution effects of wood energy and wood-based products (Hurmekoski *et al.,* 2020). The carbon balance was calculated as the change in the carbon stocks of forest biomass, soil organic matter and wood-based products minus the carbon releases of harvesting, transport and manufacturing plus the substitution effects of wood-based products (avoided emissions from fossil fuels and fossil-based products due to the use of wood). A positive balance means that forestry is a carbon sink. The pools were the same as those listed in the Intergovernmental Panel on Climate Change's carbon accounting rules (Aalde *et al.,* 2006), including living forest biomass, soil organic matter and wood-based products (Heinonen *et al.,* 2017). Biomass was calculated by the models of Repola *et al.* (2007) and Repola (2009). The amount of carbon in the living biomass was estimated by assuming that 50 per cent of the dry biomass is carbon (Pukkala, 2014). The carbon release from soil was estimated using the Yasso07 model (Liski *et al.,* 2009). The inputs to the soil carbon pool consisted of dead trees, harvest residues, annual above- and belowground litter yield and the growth of peat in non-drained peatlands (Pukkala, 2014). Litter production was calculated using tree-species-specific turnover rates (Pukkala, 2014).

The decay of the stems of dead trees was simulated using annual decomposition rates, predicted separately for each dead tree (Pukkala, 2006). The decomposition rates were predicted using a model based on the decay information available in Tikkanen *et al.* (2007). Broadleaf (mainly birch) volume and the dry mass of the stems of standing and downed dead trees were calculated at 10-year intervals, and the mean values over the 100-year simulation period were used as biodiversity indicators.

Optimization

A total of 200 different landscape-level plans were developed by combining the management schedules simulated for the stands. The plans maximized a multi-objective utility function that included the following management objectives and related indicators (in parentheses): (1) carbon sequestration (forestry carbon balance (t)); (2) biodiversity (amount of deadwood (t) and broadleaf volume (m^3)); (3) economic profitability of forestry (NPV (€)) and (4) timber supply to industry (volume of harvested timber (m^3)). In each plan, we randomly assigned different weights to these five indicators of the four ecosystem services. The weights were drawn from a uniform distribution and were scaled so that their sums were equal to one.

Additional 50 optimizations were conducted using each pair of indicators as management objectives and varying their weights. These 50 optimizations resulted in a production possibility frontier for each pair of ecosystem service indicators. The trade-offs and correlations among ecosystem services were evaluated by plotting the production possibility curves and the values of the ecosystem service indicators in the 200 plans in pairs, and by calculating the Pearson correlation coefficient for each pair of indicators. Production possibility curves were produced from the optimization runs, where the utility function included only two ecosystem service indicators at a time. The curve was termed concave or convex, according to Figure 1.

The optimal combination of treatment schedules was found by using the simulated annealing heuristic (Bettinger *et al.,* 2002; Lockwood and Moore, 2006). The optimization problem was formulated as follows:

$$\max U = \sum_{k=1}^{5} w_k u_k \left(\mathrm{ES}_k\right) \tag{1}$$

subject to

$$\mathrm{ES}_k = \sum_{j=1}^{n} \sum_{i=1}^{n_j} x_{ij} \mathrm{ES}_{ijk} \quad k = 1, \ldots, 5$$
$$\sum_{i=1}^{n_j} x_{ij} = 1 \qquad j = 1, \ldots, n$$
$$x_{ij} = \{0, 1\}, \tag{2}$$

where $\boldsymbol{w_k}$ is the weight and $\boldsymbol{u_k}$ is the sub-utility function for ecosystem service indicator k; ES_k is the total amount of indicator k; ES_{ijk} is the amount of indicator k in treatment schedule i of stand j; n is the number of stands and n_j is the number of treatment schedules simulated for stand j; and x_{ij} is a 0–1 variable indicating

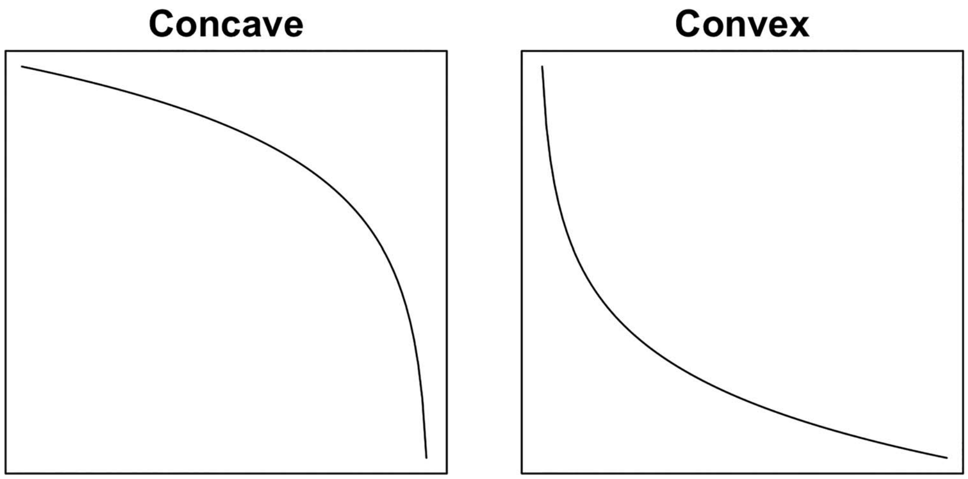

Figure 1 Concave and convex trade-off curves.

whether treatment schedule i of stand j is included in the solution ($x_{ij} = 1$ for the schedule that is included in the solution). The sub-utilities were calculated by normalizing the value of the objective variable by its greatest possible value (single-objective maximum). Since the sub-utility functions were linear, their only role was to standardize the values of ecosystem service indicators to the same range where the maximum value was equal one. The optimization was implemented in the simulation-optimization software Monsu (Pukkala, 2004).

Comparison of single- and multi-objective plans

The equality of the weights of the five ecosystem service indicators was described using the Gini index (Gini, 1921). A low Gini index means that the five weights are almost equal, while a high value implies that most of the weight is on one indicator. Plans in which the weights of the five ecosystem service indicators were nearly equal represented multi-objective forestry, whereas plans, where most of the total weight was on one objective, represented single-objective management. In a part of our analyses, we classified the utility functions as multi-objective when the Gini index of the weights was smaller than 0.3, and single-objective when the Gini index was greater than 0.7. Utility functions where the Gini index was between 0.3 and 0.7 were not included in these analyses.

The effect of multifunctionality (i.e. equality of the weights of the ecosystem service indicators) on the overall level of ecosystem service provisioning was estimated by calculating the mean normalized value of the indicators and plotting this against the Gini index. To calculate the relative value, the quantity of each service was divided by the maximum amount of service among the 200 plans. The mean of the five normalized values was used as a measure of the overall level of ecosystem services.

Results

Trade-offs and correlations between ecosystem services

The correlation coefficients between the ecosystem services ranged from −0.8 to 0.9 (Figure 2). The shape of the production possibility frontier for the pairs of ecosystem services was always concave, indicating an increasing marginal rate of transformation. Economic profitability (NPV) correlated positively with the volume of harvested timber and broadleaf volume and negatively with the amount of deadwood and the forestry carbon balance. Despite positive correlations between NPV, harvested volume and broadleaf volume among the 200 Pareto optimal multi-objective plans, these indicators yielded trade-offs when any of these indicators reached a near-maximal level. This means that two or several ecosystem services may, in general, be complementary, but their relationship turns competitive when approaching their maximum production levels.

Increasing harvested volume or NPV decreased the amount of deadwood and the forestry carbon balance; however, the concave shape of the production frontiers also suggests that, in this case, a simultaneous production of the services that correlated negatively might be more efficient than having different areas for different services as done in zoning. Broadleaf volume correlated weakly with the other indicators. This means that a reasonable volume of broadleaf trees can be maintained in forests without any significant decrease in the supply of other ecosystem services.

Forestry carbon balance correlated strongly and positively with the amount of deadwood, competing with it only at near-maximal values. Carbon balance correlated negatively, but weakly so, with broadleaf volume. The negative correlation was stronger with harvested volume and especially with NPV. Also, the trade-off curve suggests strong competition between economic profits from timber sales and the amount of deadwood in forests.

Production level of ecosystem services in single- and multi-objective forestry

Multi-objective plans with low Gini indices produced higher average levels of ecosystem services than plans where most of the total weight was given to a single objective (high Gini index) (Figure 3). The level of ecosystem services varied substantially between management strategies, especially when the Gini index was high (Supplementary Figure 1). However, solutions, where

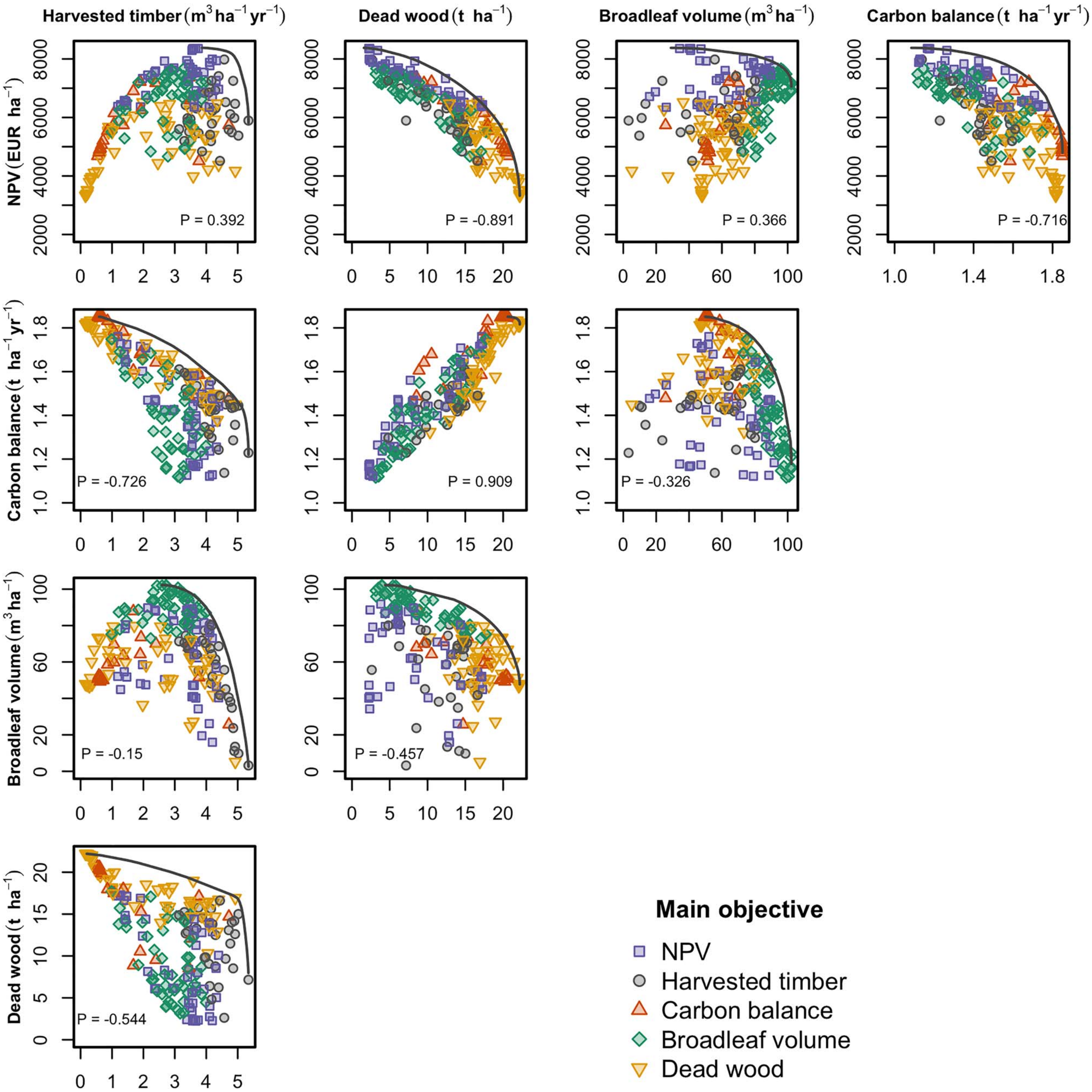

Figure 2 Ecosystem service values (dots) and production possibility boundaries (continuous lines) for pairs of ecosystem services. The scatter plots and correlations are based on 200 Pareto optimal plans. Each plan is categorized according to its main objective, the main objective being the ecosystem service with the highest weight in a multi-objective optimization problem. The *P* values are Pearson correlation coefficients among the 200 plans. This figure appears in colour in the online version of *Forestry*.

carbon balance had a high weight, produced a high overall level of all ecosystem services (triangles with high Gini indices in Figure 3), whereas solutions, where NPV or harvested volume had a high weight, were often detrimental to other ecosystem services (Figure 3). Multi-objective management provided higher average values for NPV, harvested volume and broadleaf volume, whereas the average carbon balance and deadwood volume were nearly the same in multi-objective plans and those that were classified as single-objective (Figure 4).

Carbon balance and the amount of dead wood had a strong positive correlation with each other; both correlating negatively with the other ecosystem services (with the exception of broadleaf volume correlating positively with harvested volume). Therefore, we also compared two utility functions: the first depending on carbon balance and the amount of dead wood, and the other depending on the remaining three indicators. Figure 5 shows slightly concave trade-off curve between the two utility functions, suggesting that these groups of ecosystem

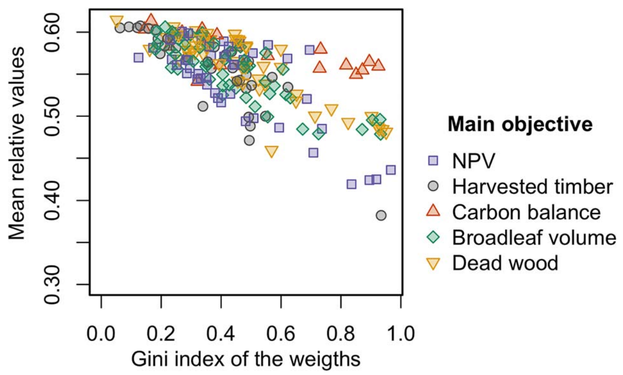

Figure 3 Mean relative values of ecosystem services among 200 Pareto optimal plans as a function of the multifunctionality of management objectives. A low Gini index implies that the weights of the five management objectives are nearly equal, while a high Gini index implies that one objective dominates. 'Main objective' is the variable that has the highest weight in the utility function. This figure appears in colour in the online version of *Forestry*.

services should be produced simultaneously in the same forest landscape. On the other hand, the correlation between the two utility functions was very strong and negative, which means that assigning separate areas for the two utilities would be almost equally efficient (Figure 5).

Discussion

Increasing demands to produce high amounts of several ecosystem services in forests (Reid *et al.*, 2005) requires knowledge of their trade-offs and correlations. In this study, we evaluated the relationships and production levels of five objective variables that were assumed to be indicators of four ecosystem services. To confirm that multi-objective forest management would produce higher average amounts of ecosystem services, we developed an innovative approach where the degree to which the random objective functions were multi-objective was measured with the Gini index. The management plans analysed in this study ranged from multi-objective plans where the weights of all ecosystem services were nearly equal, to plans in which one ecosystem service had most of the weight. The results were calculated for a period of 100 years, as the immediate provision level of an ecosystem service may be different from the average of a longer period due to temporal changes in forest structure (Rodriguez *et al.*, 2006).

Instead of using pre-defined preferences for different management objectives (see Seidl and Lexer, 2013; Langner *et al.*, 2017; Marto *et al.*, 2018), we used a large pool of random preferences and analysed 200 different combinations of objective weights. The set of the 200 optimal plans showed, for example, that some ecosystem service indicators were complementary in most situations and turned competitive only at near-maximal production levels (e.g. deadwood and carbon balance). Some other ecosystem services were competitive at all production levels (e.g. economic profitability and deadwood volume).

Other studies have evaluated the trade-offs of selected ecosystem services for specific management plans (Triviño *et al.*, 2015; Pohjanmies *et al.*, 2017b). We employed multi-attribute utility theory and numerical optimization for the trade-off analyses. Trade-offs between ecosystem services may depend on the spatial scale of the analysis (Chan *et al.*, 2006; Burton *et al.*, 2010; Gamfeldt *et al.*, 2013; Irauschek *et al.*, 2017). In this study, we used a forest-landscape-level analysis, which has been shown to offer benefits in the simultaneous production of multiple objectives (Mönkkönen *et al.*, 2014; Felipe-Lucia *et al.*, 2018). One reason for this benefit is that competition among services may be lower in a larger area (Felipe-Lucia *et al.*, 2018) because it may be possible to vary the production levels of different services temporally and from one stand to another, depending on the features and production potentials of each stand at different time points.

Our study supports the hypothesis that multi-objective forest management increases the overall production levels of most studied ecosystem services in boreal forest landscapes, compared with 'zoning', where different forest areas are assigned for different ecosystem services. This conclusion is supported by the concave shape of their trade-off curves (Kangas and Pukkala, 1996; Pukkala, 2002, 2014). In the optimization approach used in this study, many alternative management schedules are simulated in each stand, and their best combination is selected using combinatorial optimization. Optimization may choose schedules that maximize a single ecosystem service, or schedules that are compromises between several services. Since this method allows more options than zoning, but zoning is not ruled-out in optimization, it can be assumed that the method used in our study provides more efficient forest management plans than strict zoning.

It can be expected that some zoning will also occur when a management plan is compiled by combinatorial optimization, as was done in our study. This means, for example, that timber-production-oriented management schedules would be selected for some-specific stand types, while some other stand types might have prescriptions where much carbon is accumulated in tree biomass and forest soil. The optimal solution of a forest planning problem may include different degrees of stand-level multifunctionality, where some stands might produce mainly one benefit and some other stands may yield more equal amounts of several benefits.

Our results showed that carbon sequestration and provisioning of deadwood in the forest had a strong positive correlation. Both of them correlated negatively with the volume of harvested timber and economic profitability of forestry (Schwenk *et al.*, 2012; Triviño *et al.*, 2015; Pohjanmies *et al.*, 2017b). Harvesting less results in higher carbon stocks in the forest biomass and soil, which cannot be compensated for by the carbon stocks and substitution effects of wood-based products (Seppälä *et al.*, 2019). Reduced harvest levels also increase tree mortality and subsequently, the amount of deadwood in forests, through increased competition of growing resources and aging of in forest stands (Tikkanen *et al.*, 2007; Alrahahleh *et al.*, 2017; Heinonen *et al.*, 2017).

The possibility to use optimally the production potentials of each stand is the main reason why different ecosystem services compete less at the forest level than at the stand level. Previous studies with alternative approaches have also shown that if the habitat requirements of different species are taken into account

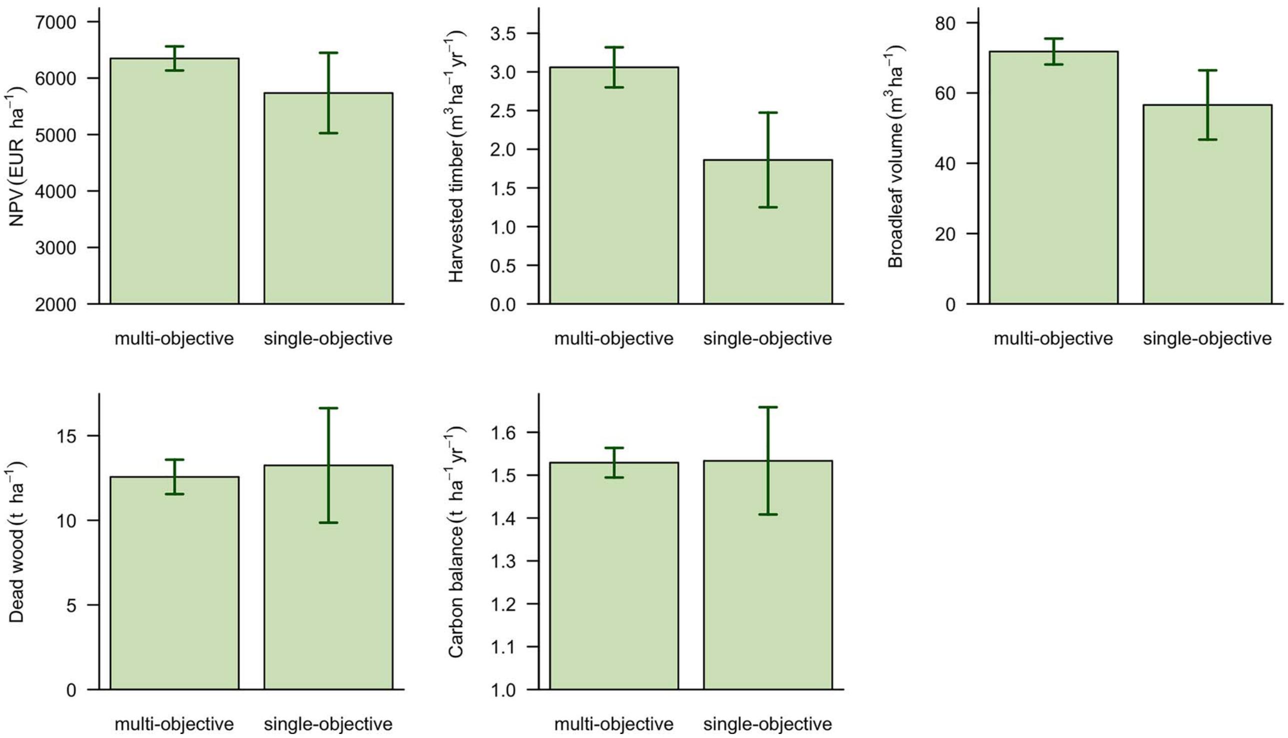

Figure 4 Average amounts of ecosystem services in multi-objective (Gini index <0.3) and single-objective (Gini index >0.7) optimizations. This figure appears in colour in the online version of *Forestry*.

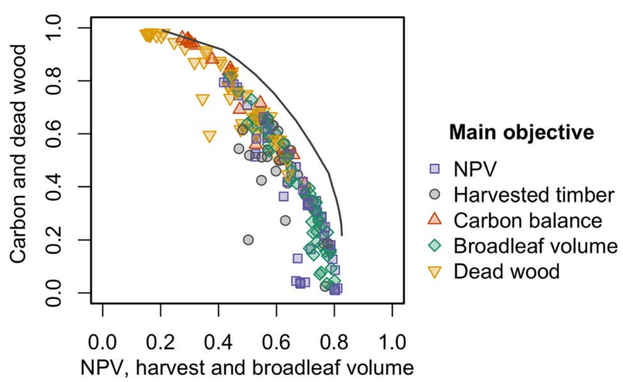

Figure 5 Relationship between utility functions, where utility depends on carbon balance and deadwood volume (*y*-axis) or on NPV, harvested volume and broadleaf volume (*x*-axis) among 200 Pareto optimal plans. The line represents the production possibility frontier between the two selected utility functions. This figure appears in colour in the online version of *Forestry*.

in the evaluation of forest biodiversity, optimization would also find set-aside stands without any cuttings (Mönkkönen *et al.*, 2011).

Our innovative study approach showed that the production of several ecosystem services is more efficient in multi-objective forestry. The outcome was anticipated, as the decreasing marginal productivity applies to most services and production factors (Kangas and Pukkala, 1996; Pukkala, 2002, 2014). The overall production level of all the ecosystem services decreases as the Gini index increases (i.e. as one single ecosystem service dominates in the objective function). In this study, we concentrated on the quantities of five numerical indicators of four ecosystem services. Utility functions were used as a technical means of obtaining different Pareto optimal combinations of the analysed indicators (Borges *et al.*, 2014). However, our utility functions did not represent the preferences of society, the forest landowner or any other true decision-maker as in other studies (Langner *et al.*, 2017; Marto *et al.*, 2018). Instead, we produced a large set of preferences to analyse the effect on management objectives on the amount of ecosystem services.

In our analyses, the sub-utility functions of the different ecosystem services were assumed linear. It implies that utility increases linearly and indefinitely when the value of the indicator variable increases. The true preferences of people are seldom linear functions of the quantity of the management objective. In most cases, the preferences of people follow decreasing marginal utility, where each additional unit of a forest product or ecosystem service increases utility less than the previous unit. The same applies to the relationship between biodiversity indicators and biodiversity. For example, when the amount of deadwood is scant, each additional cubic meter of deadwood may improve biodiversity values significantly, but when dead wood is plentiful, biodiversity no longer benefits from additional deadwood. Decreasing marginal utility leads to a situation where a simultaneous production of several ecosystem services is optimal even when the trade-off curves between the services are not concave. This strengthens our conclusion that, in boreal forested landscapes, the utility that forests give to society is maximized when forestry is multi-objective.

Conclusion

An increasing demand for multiple ecosystem services obliges societies to opt for multi-objective forest management. Uncertainties related to climate change, forest disturbances (Seidl *et al.,* 2017) and the future preferences of society (Seidl and Lexer, 2013) call also for more diversified management. Our innovative approach made it possible to analyze, numerically and objectively, the effect of multi-objective management on the production of several ecosystem services. Our trade-off analyses showed that forestry carbon balance and the amount of deadwood correlated positively with each other, and both of them correlated negatively with harvested timber volume and economic profitability of forestry. Despite this, the simultaneous maximization of multiple objectives increased the overall production levels of several ecosystem services. Hence, we suggest that the management of boreal forest landscapes should be multi-objective to sustain the simultaneous provision of timber and other ecosystem services. This conclusion is further strengthened by the assumption of decreasing marginal utility. Summarizing, this means that forestry that produces a balanced mix of several ecosystem services would maximize the benefit of current and future societies. The study approach could be further extended by considering effects of ecosystem service preferences that vary over time.

Supplementary data

Supplementary data are available at *Forestry* online.

Conflict of interest statement

None declared.

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