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Optimizing management to enhance multifunctionality in a boreal forest landscape

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Running title: Timber, carbon and biodiversity trade-offs

Summary

1. The boreal biome, representing approximately one third of remaining global forests, provides a number of crucial ecosystem services. A particular challenge in forest ecosystems is to reconcile demand for increased timber production with provisioning of other ecosystem services and biodiversity. However, there is still little knowledge about how forest management could help solve this challenge. Hence, studies that investigate how to manage forests to reduce trade-offs between ecosystem services and biodiversity are urgently needed to help forest owners and policy-makers take informed decisions.
2. We applied seven alternative forest management regimes using a forest growth simulator in a large boreal forest production landscape. First, we estimated the potential of the landscape to provide harvest revenues, store carbon and maintain biodiversity across a 50-year time period. Then, we applied multiobjective optimization to identify trade-offs between these three objectives, and to identify the optimal combination of forest management regimes to achieve these objectives.
3. It was not possible to achieve high levels of either carbon storage or biodiversity if the objective of forest management was to maximize timber harvest revenues. Moreover, conflicts between biodiversity and carbon storage became stronger when simultaneously targeting high levels of timber revenues. However, with small reductions of timber revenues it was possible to greatly increase the multifunctionality of the landscape, especially the biodiversity indicators.
4. Forest management actions, alternative to business-as-usual management, such as reducing thinnings, extending the rotation period and increasing the amount of area set-aside from forestry may be necessary to safeguard biodiversity and non-timber ecosystem services in Fennoscandia.
5. *Synthesis and applications*. Our results show that no forest management regime alone is able to maximize timber revenues, carbon storage and biodiversity individually or simultaneously, and that a combination of different regimes is needed to resolve the conflicts among these objectives. We conclude that it is possible to reduce the trade-offs between different objectives by applying diversified forest management planning at the boreal landscape-level and that we need to give up the all-encompassing objective of very intensive timber production, which is prevailing particularly in Fennoscandian countries.

Key-words: biodiversity; carbon; climate change mitigation; climate regulation; ecosystem services; Finland; forest planning; multiobjective optimization; timber; trade-offs

Introduction

Boreal forests, representing approximately one third of remaining global forests, provides a number of crucial ecosystem services (e.g., Bradshaw, Warkentin & Sodhi 2009; Hansen, Stehman & Potapov 2010). Timber production is the most economically valuable provisioning service in boreal forests, constituting approximately 45% of the world's stock of growing timber (Vanhanen *et al.* 2012). However, increasing concerns about biodiversity loss and global change have intensified efforts to manage forests for multiple ecosystem services and functions (Biber *et al.* 2015). One of the critical functions of forests is to store and sequester carbon, which contributes to climate regulation as boreal forests store about one third of the global terrestrial carbon (Pan *et al.* 2011). Depending on how forests are managed they can act as net carbon sources or sinks and play an important role in climate change mitigation (e.g., Birdsey, Pregitzer & Lucier 2006). For example, it seems that Europe's managed forests have been a source of carbon for the past 250 years, contributing to climate warming rather than mitigating it (Naudts *et al.* 2016). In addition, boreal forests provide a diversity of important services such as collectable goods and water regulation among others (Saastamoinen *et al.* 2013). Moreover, forest biodiversity is an important source of food as well as recreational and aesthetic values (Ehrlich & Ehrlich 1992).

Biodiversity and ecosystem services are intrinsically associated but the relationship between them is complex because biodiversity plays an important role at many levels of ecosystem service production (Mace, Norris & Fitter 2012). It still remains unclear how ecosystem services relate to biodiversity and to what degree the conservation of biodiversity will ensure the provision of ecosystem services and vice versa (Cardinale *et al.* 2012; Harrison *et al.* 2014). A recent review (Cimon-Morin, Darveau & Poulin 2013) showed that positive relationships were common between regulating services (e.g., climate regulation) and biodiversity, whereas negative relationships dominated between provisioning services (e.g., food) and biodiversity. Spatial scale also plays a key role as a positive relationship between biodiversity and regulating services has been found at a global scale (e.g., Strassburg *et al.* 2010) but the relationship seems to become weaker at national or regional scales (e.g., Thomas *et al.* 2013). Understanding when biodiversity conservation and ecosystem services maintenance are compatible is one of the main aims of the International Panel of Biodiversity and Ecosystem Services (IPBES) (Balvanera *et al.* 2014).

Different methodologies have been used to examine trade-offs between biodiversity and ecosystem services like multi-criteria decision analysis (Schwenk *et al.* 2012), InVEST (Sharp *et al.* 2014), ARIES (Villa *et al.* 2014) or Zonation (Thomas *et al.* 2013) among others. However, multiobjective optimization (Miettinen 1999) is a flexible tool that allows not only to compare the output of different management regimes or scenarios but to identify a combination of management regimes that will be needed to optimally deliver both biodiversity and ecosystem services. Until now, this methodology has been applied to target two objectives simultaneously. Mönkkönen *et al*.(2014) explored trade-offs between timber revenues and biodiversity in a boreal production forest while Triviño et al. (2015) analysed trade-offs between timber revenues and carbon storage/sequestration in the same landscape. Identifying and visualizing trade-offs between more than two objectives simultaneously is still a challenge in this field of research.

Finland is the most forested country in Europe and in the boreal zone (UNEP FAO and UNFF 2009) with around 76% of its land area covered by forests, most of which are under commercial management (Finnish Forest Research Institute 2011). These forests have been intensively managed, within-stand forest structure has become relatively even-aged and the amount of deadwood has been considerably reduced (e.g., Vanha-Majamaa *et al.* 2007). Management practices have an effect on the delivery of ecosystem services by altering forest structure (e.g., reducing amount of deadwood which is an important resource and habitat for biodiversity) and function (e.g., carbon sequestration). Previous studies have shown that the frequency and intensity of thinning play very important roles in timber production and carbon sequestration (Hynynen *et al.* 2005; Cao, Valsta, Mäkelä 2010), yet widely applied thinning practice in Finland also reduces structural diversity important to biodiversity (Mönkkönen *et al.* 2011; Tikkanen *et al.* 2012). Extending the time of final harvest is also an effective management action to increase forest carbon sequestration (Liski *et al.* 2001; Hynynen *et al.* 2005; Triviño *et al.* 2015).

Here, we examined trade-offs between timber, carbon storage and biodiversity across a large boreal forest production landscape in central Finland. We incorporated forest dynamics by simulating forest growth across 50-years for seven alternative management regimes. We used market prices to estimate the net present value of harvest revenues to measure the economic value of timber production. We estimated the volume of carbon stored across the 50-year time period. Finally, we used two complementary indicators of biodiversity: (i) volume of deadwood as it is the main resource for a large range of endangered species in boreal forests (Tikkanen *et al.* 2006) and (ii) the habitat availability of six vertebrate species that represent a wide range of habitat types. We then applied multiobjective optimization for analysing trade-offs among these different objectives. These analyses can identify situations where the current management actions are inefficient at providing multiple goods or services and where biodiversity or carbon storage can be increased with minimum reductions in timber production, or vice versa. Specifically, we address the questions: (i) What is the potential of the forest landscape to simultaneously produce timber, regulate climate and maintain biodiversity? (ii) How can forest management help achieving this multifunctionality?

Materials and methods

STUDY AREA

Our study area represents a typical Finnish production forest landscape located in Central Finland (Fig. 1). The total area is 68,700 hectares with forests covering the majority of the landscape and the rest covered by lakes, peatlands and agricultural lands. Scots pine (*Pinus sylvestris*), Norway spruce (*Picea abies*) and birch (*Betula pendula* and *Betula pubescens*) dominate the forest consisting of 29,666 stands (forest management unit) of an average size of 1.4 hectares. The age for the largest proportion (62%) of forest stands is less than 50 years at the initial conditions due to past forest management practices. The predominance of young stands is fairly typical in intensively managed forest landscapes (see Fig. S1 in Supporting Information for the distribution of forest stands' age).

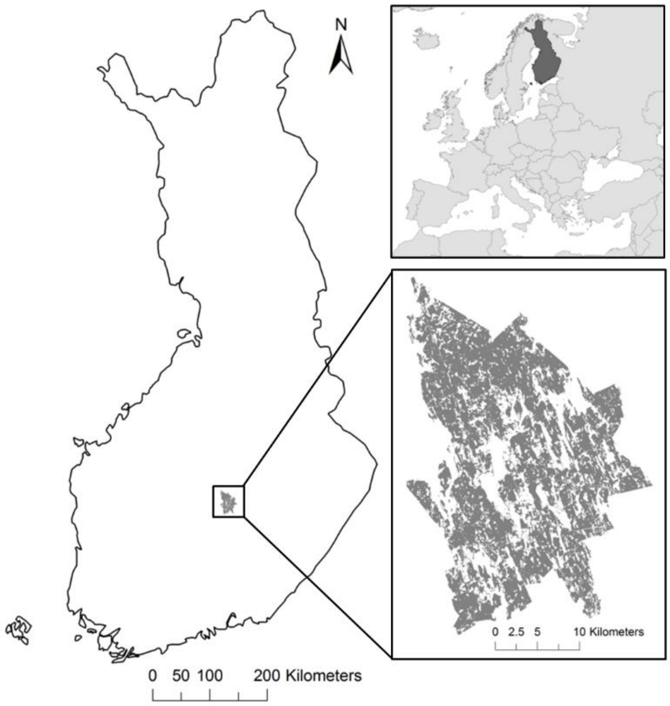

Fig. 1. Location of Finland in northern Europe and the study area in Central Finland.

FOREST DATA, MANAGEMENT REGIMES AND FOREST GROWTH SIMULATIONS

We extracted data for forest growth modelling from forest inventory data administered by the Finnish Forest Centre. We considered seven alternative management regimes for each stand that are either being implemented or considered for application in Finland by government agencies (see Table 1): the current recommended regime that targets maximal timber production (**BAU:** Business as usual); two regimes that postpone the final harvesting (**EXT10** and **EXT30**); a regime that increases the number of trees retained in the final harvest (**GTR30**); two regimes with no thinnings (**NTLR** and **NTSR**) and a regime that represents a permanent conservation strategy (**SA:** Set aside). All these management regimes have corresponding policy incentives according to which forest owners are allowed and encouraged to modify management for multiple objectives (for further details see Mönkkönen *et al.* 2014).

Table 1. Management regimes applied on the forest stands in the study area that are either being implemented or considered for application in Finland by government agencies (adapted from Mönkkönen *et al.* 2014).

Management regime	**Acronym**	**Description**
Business as usual	BAU	The current recommended regime: average rotation length 80 years; site preparation, planting or seedling trees; 1-3 thinnings; final harvest with green tree retention level 5 trees/ha
Set aside	SA	No management
Extended rotation (10 years)	EXT10	BAU with postponed final harvesting by 10 years; average rotation length 90 years
Extended rotation (30 years)	EXT30	BAU with postponed final harvesting by ≥30 years; average rotation length 115 years
Green tree retention	GTR30	BAU with 30 green trees retained/ha at final harvest; average rotation length 80 years
No thinnings (final harvest threshold values as in BAU)	NTLR	Otherwise BAU regime but no thinnings; therefore trees grow more slowly and final harvest is delayed; average rotation length 86 years
No thinnings (minimum final harvest threshold values)	NTSR	Otherwise BAU regime but no thinnings; final harvest adjusted so that rotation does not prolong: average rotation length 77 years

We ran forest growth simulations for 50 years in 5-years intervals using the MOTTI stand simulator (http://www.metla.fi/metinfo/motti/index-en.htm), which has been applied to investigate forest growth and timber yield as well as to assess profitability for alternative forest management regimes. MOTTI is a statistical growth and yield model that includes the most recent descriptions of forest processes (e.g., Hynynen *et al.* 2005; Ahtikoski *et al.* 2011; Kojola *et al.* 2012). The models used in MOTTI are based on extensive empirical data from permanent field sites and forest inventory plots also including measurements from trees older than the usual rotation lengths (see Appendix S1 for more details about MOTTI and justification of the length of the simulation period).

ECOSYSTEM SERVICES

Timber harvest revenues

As we were interested in the economic value of the extracted timber, we used the net present value (NPV) data of harvest revenues for each management regime and forest stand from a previous study (Mönkkönen *et al.* 2014). In these calculations, stumpage prices were calculated for eight timber assortments (pulp wood and saw logs for each species: Scots pine, Norway spruce and two birch species). Moreover, the unit costs of five silvicultural work components were included: (1) natural regeneration, (2) seedling, (3) planting, (4) tending of seeding stands, and (5) cleaning of sapling stands (Finnish Forest Research Institute 2012). We applied a 3% real interest rate in discounting the revenues and costs occurring at different time periods. As NPV is affected by the discount rates applied, we carried out a sensitivity analysis for 1% and 5% rates (see Table S1).

Carbon storage

Carbon storage for each management regime and forest stand was calculated as the average amount of carbon stored in living wood (tree roots, stem, branches, twigs, foliage), dead wood, extracted timber (timber taken away from the stands during thinnings and clear-cuts) and the residuals left after harvesting for the 50 years-period (for further details see Triviño *et al.* 2015).

BIODIVERSITY INDICATORS

Deadwood

Deadwood is a critical resource in boreal forests (Stokland, Siitonen & Jonsson 2012) and an indicator of forest biodiversity (Lassauce *et al.* 2011). Intensive forestry in Fennoscandia has decreased the amount of deadwood to a small fraction of its pristine levels (Siitonen 2001). In boreal Fennoscandia, 20-25% of the forest-dwelling species are dependent on deadwood habitats and they constitute 60% of red-listed species (Tikkanen *et al.* 2006). Therefore, we can use deadwood volume as a reliable and direct proxy for biodiversity and we estimated it using the following formula:

$$DW\ index = \sum_{j=1}^{N} Vol_j * (1 - D)_j,$$

where Vol_j is the total volume of deadwood in each forest stand j and $(1 - D)$ is the inverse of the Simpson's diversity index of deadwood resources across 20 different deadwood types (from 4 tree species and 5 decay stages) and varies between 0 and 0.95. Thus, *DW index* is the volume of deadwood weighted by the diversity of deadwood types, and reaches its maximum when total deadwood resources are evenly distributed among the 20 categories. By taking into account both volume and diversity of deadwood types, the measure is more likely to be a good indicator of deadwood-inhabiting biodiversity (Lassauce *et al.* 2011). The deadwood volume (weighted by diversity) for each management regime and stand was calculated as the average amount of deadwood for the 50-years period.

Species habitat availability

In order to bring complementary information on biodiversity, we also combined the habitat availability of six vertebrate species: capercaillie (*Tetrao urogallus*), flying squirrel (*Pteromys volans*), hazel grouse (*Bonasia bonasa*), long-tailed tit (*Aegithalos caudatus*), lesser-spotted woodpecker (*Dendrocopos minor*) and three-toed woodpecker (*Picoides tridactylus*). These species were selected to represent a wide range of habitat types as well as social and economic values including game birds, umbrella and threatened species. The habitat suitability model results were taken from Mönkkönen et al. (2014) and were based on literature and expert opinion about the habitat requirements of the focal species. The habitat suitability index (HSI) for a species varies between 0 (unsuitable habitat) and 1 (most suitable habitat) and is related to the probability of the presence of the species in the stand. We thus calculated a combined habitat suitability index for the six species analogously to the combined probability of independent events:

Combined Habitat Suitability Index = $1 - \prod_{i=1}^{6}(1 - HSI_i)$

As the HSI of a species is related to the probability of the presence of the species, the combined HSI is related to the probability that at least one of the species is present. This measure provides a high value, close to one, for a stand if at least one of the species has high HSI and a value close to zero if a stand provides low suitability for all the species. Therefore, this way of combining the HSI ensures that we can identify stands with suitable habitat at least for one of the target species and stands that have low value as habitat for all of the species (see Appendix S2 for further information). Finally, the combined habitat availability was calculated by multiplying Combined Habitat Suitability Index with stand area. The combined habitat availability for each management regime and stand was calculated as the average amount of habitat availability for the 50-years period.

MULTIOBJECTIVE OPTIMIZATION

To reveal the relationships among the objectives (timber harvest revenues, carbon storage and biodiversity), we used the methodology of multiobjective optimization (see e.g., Miettinen 1999). We formulated the multiobjective optimization problem of forest management as maximizing the three objectives (objective functions) on the set of all possible management plans which can be implemented in the landscape. A management plan is defined as a combination of the seven available management regimes across stands. It is impossible to achieve maximal values for all the objectives simultaneously when there is even a slight conflict among objectives. Thus, the solution to the optimization problem is a set of Pareto optimal plans. A plan is Pareto optimal if the outcome cannot be improved for any objective without deteriorating at least one of the other objectives. We used the ε-constraint method (Miettinen 1999) for deriving Pareto optimal solutions (see Appendix S3 for detailed mathematical formulation of the multiobjective optimization problem). For further details of the formulation of the multiobjective optimization model and the concept of Pareto optimality connected to analysing trade-offs, see Mönkkönen et al. (2014). The optimization calculations were carried out using IBM ILOG CPLEX optimizer (http://www-01.ibm.com/software/commerce/optimization/cplex-optimizer/).

We solved the multiobjective optimization problem for each pair of objectives (bi-objective optimization) as well as for all three objectives (tri-objective optimization). We used bi-objective optimization to analyse the severity of trade-offs between pairs of objectives, and tri-objective optimization to analyse how these pairwise trade-offs change while a third objective is also targeted. Specifically, we examined how trade-offs between carbon storage and biodiversity changed when different levels of timber harvest revenues were required to be achieved at the same time. These requirements modelled as constraints on NPV, ranged from maximal timber harvest revenues (NPV not less than 99.9% of its maximum), to moderate losses (99%, 95%, 90%, or 80% of its maximum), to no pre-set requirement (no constraints). Then, for each tri-objective problem, we identified a single compromise (joint production) solution, i.e. management plan that, while guaranteeing the required level of timber harvest revenues, results in the smallest losses in both carbon storage and biodiversity from their respective maximums. We compared these compromise management plans in terms of the allocation of the alternative management regimes within them. Finally, we further explored the allocation of regimes for a single Pareto optimal set (95% of timber NPV) for three management plans: (i) compromise solution, (ii) maximize carbon storage and (iii) maximize biodiversity indicators. The 95% NPV level was selected because in practice the Finnish society has shown willingness to give up 5% of the maximum timber production for environmental reasons (see Mönkkönen *et al.* 2014).

Results

POTENTIAL TO PROVIDE TIMBER REVENUES, STORE CARBON AND MAINTAIN BIODIVERSITY

The maximum capacity of the landscape: (i) to provide harvest revenues (NPV) was 250 M€ (average 5,800 €/ha), (ii) to store carbon was 4,459 10^3MgC (average 103 MgC/ha), (iii) for deadwood index was 218,150 m^3 (average 5.1 m^3/ha) and (iv) for combined habitat availability was 20,211 (no units) (average 0.47/ha).

The potential to provide ecosystem services and maintain biodiversity differed among forest management regimes when applying each single one of them consistently. The differences among the maximum levels achieved by each regime were larger for carbon storage and biodiversity indicators than for timber revenues (Fig. 2). The recommended regime (BAU) provided the highest NPV closely followed by increasing tree retention (GTR30) and the two no-thinning regimes. Nevertheless, all management regimes provided quite high NPV values (above 185 M€) with the exception of set-aside which by definition provided no harvest NPV. The single management regime that clearly provided the highest potential to store carbon and maintain high levels of biodiversity but the lowest NPV was set-aside (Fig. 2). The second management regime that increased the amount of stored carbon was to extend the final harvesting by 30 years (EXT30). The two no-thinning regimes were also very beneficial for both biodiversity indicators but especially for volume of deadwood. There was no single management regime that, if applied consistently, maximized the ecosystem services and biodiversity indicators analysed (see horizontal dashed line in Fig. 2). Even for harvest revenues, an optimal combination of management regimes provided higher value than the consistent application of the recommended regime (BAU). Therefore, a combination of forest management regimes is needed to obtain the maximum values.

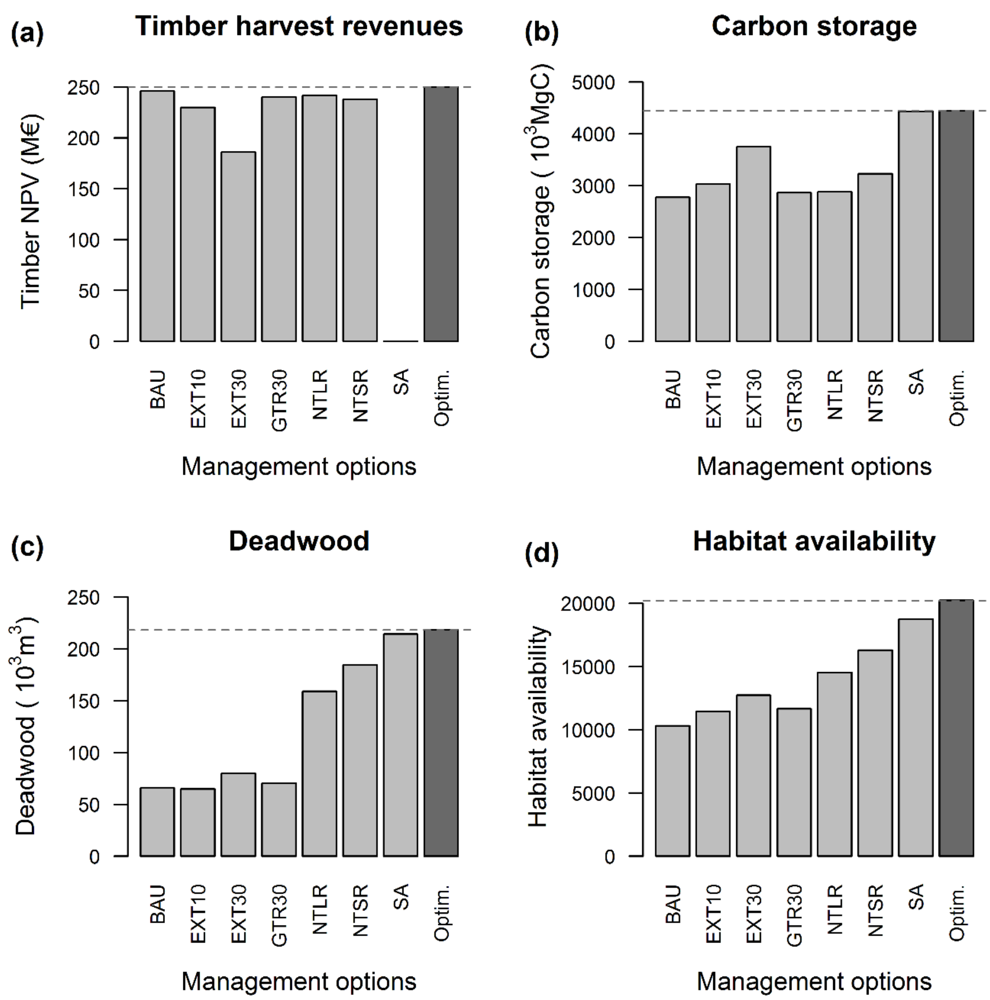

Fig. 2. Bar plots summarizing landscape results of: (a) timber harvest revenues (NPV) (€), (b) carbon storage (MgC), (c) deadwood index (m^3) and (d) habitat availability (no units) for alternative management regimes if applied consistently across all the stands and the Pareto optimal plan (dark grey bar). The acronyms of the management regimes are the same as in Table 1. Optim. represents the maximum achievable value by combining different management plans. The horizontal dashed line allows comparing the optimal solution (Optim.) with the maximum levels achieved for each management regime.

MULTIOBJECTIVE OPTIMIZATION: TRADE-OFFS BETWEEN HARVEST REVENUES, CARBON STORAGE AND BIODIVERSITY

In the set of Pareto optimal plans, we found that the pairwise trade-offs between timber NPV and biodiversity were stronger than between carbon storage and biodiversity (see Appendix S2 and Fig. S2 for further information). Regarding the multiobjective optimization, the required level of timber

NPV had a substantial effect on the trade-offs between carbon storage and biodiversity. The Pareto optimal curves show that when the requirement was to maximize NPV (Fig. 3: Timber 99.9%) only some 39-46% of the maximum deadwood, 61-64% of the habitat availability and 65% of carbon storage could be achieved. However, when giving up 1 to 5% of NPV the situation for biodiversity could be improved dramatically (47-90% of the maximum deadwood and 65-88% of the habitat availability) but not so much for carbon storage (66-77%).

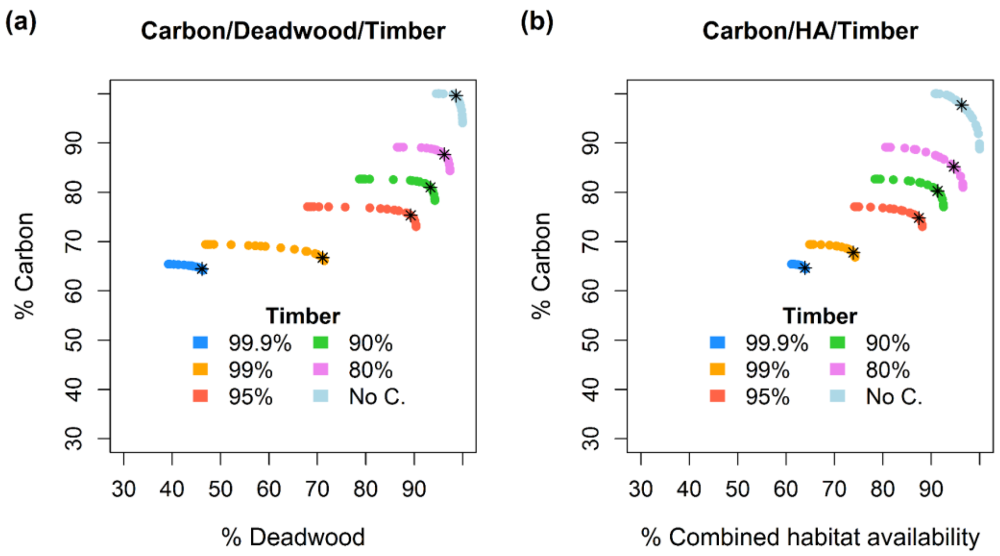

Fig. 3. Multiobjective optimization results: curves representing the trade-offs between carbon storage and the two biodiversity indicators [(a) (deadwood index and (b) combined habitat availability)] for different levels of timber harvest revenues. The black star in each Pareto optimal set indicates the compromise management plan.

OPTIMAL COMBINATIONS OF FOREST MANAGEMENT REGIMES

The management plan that maximized timber NPV was a combination of business as usual (applied in 44% of the stands), no-thinnings (40%) and green tree retention (7%) regimes (Table 2). We examined how the percentage of stands allocated to alternative management regimes changed for the compromise outcome for biodiversity and carbon storage with decreasing levels of NPV, from the maximum value (99.9% NPV) to 'no constraints' (achieving 3-29% of the maximum NPV value).

We found that the optimal combination of regimes followed the same trend irrespectively of the biodiversity indicator (Fig. 4 A and B). The highest share was for no-thinning short rotation regime (NTSR) with 36-55% for all timber levels except for no constraints. The percentage share of the recommended regime (BAU) constantly decreased with decreasing NPV objective up to values close to zero whereas the share of other regimes increased. The share of set-aside was very low until there were no required constraints for timber, where its value rose sharply to 90% (Fig. 4).

Table 2 Percentage of area allocated for the different management practices at the 95% level of the maximum NPV. Results for three outcomes of the Pareto optimal set when: (i) maximizing both carbon and biodiversity (compromise solution), (ii) maximizing carbon (carbon specialization) and (iii) maximizing biodiversity (biodiversity specialization). The first row gives the reference solution, i.e. the share when the target is to maximize NPV.

	% Area of applied management regime						
	BAU	**SA**	**EXT10**	**EXT30**	**GTR30**	**NTSR**	**NTLR**
For maximizing NPV	44.1	0.1	8.6	0.3	6.9	36.2	3.9
For compromise outcome							
Deadwood vs Carbon	16.7	0.5	7.6	4.6	3.2	49.2	18.2
Habitat availability vs Carbon	7.3	0.1	6.7	6.0	7.3	55.5	17.2
For carbon specialization	23.1	0.1	10.2	9.9	2.5	40.2	14.0
For biodiversity specialization							
Deadwood vs Carbon	11.3	0.9	6.3	1.9	6.5	55.6	17.5
Habitat availability vs Carbon	5.5	0.2	5.1	5.3	9.8	58.7	15.3

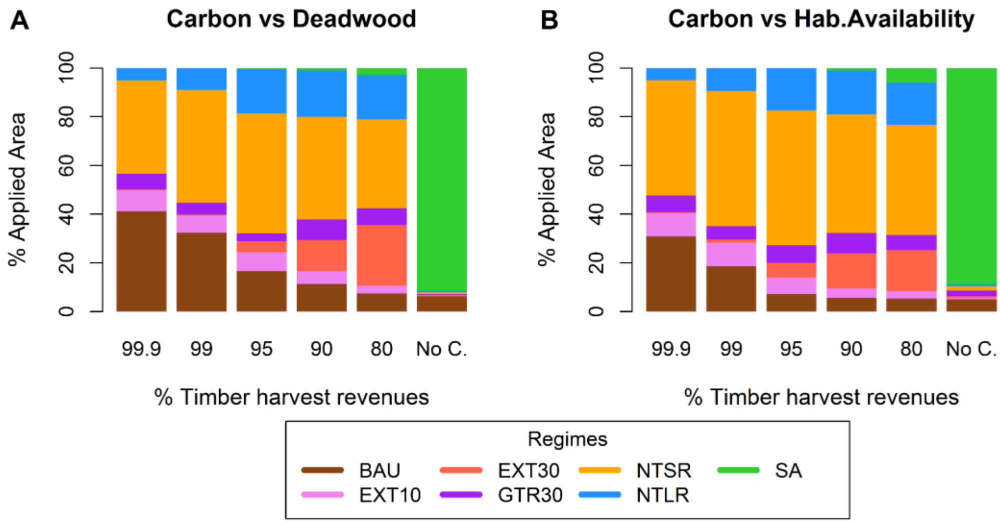

Fig. 4. Changes in percentage of area in the landscape allocated for the different management regimes for the compromise outcome in the Pareto optimal set (the black stars from Fig. 3) at decreasing levels of timber harvest revenues (from 99.9% to 'no constraints'). The acronyms of the management regimes are the same as in Table 1.

We further analysed the allocation of regimes for a single Pareto optimal set (95% of maximum NPV) comparing joint production versus specialization of the objectives. For the compromise solution about 28-32% increase in the total share of the no-thinning regimes was required at the expense of the recommended management (BAU) (Fig. 4, Table 1). However, for maximizing carbon about 11% increase in the extended rotation regimes and about 10% in NTLR was required mainly at the expense of the BAU. Finally, for maximizing any of the two biodiversity indicators also about 30-35% increase in the total share of the no-thinnings will be required (Table 2).

Discussion

We provide a powerful analytical framework that combines forest simulations with multiobjective optimization to analyse trade-offs among multiple objectives and how they can be simultaneously accommodated. We found strong trade-offs between provisioning services (timber) and both regulating services (carbon storage) and biodiversity. However, trade-offs between regulating services (carbon storage) and biodiversity were moderate, which is in line with previous literature (Raudsepp-Hearne, Peterson & Bennett 2010; Maskell *et al.* 2013). As a consequence, it was not possible to have high levels of carbon storage and biodiversity if timber revenues (NPV) were maximized. Moreover, adding the timber objective aggravates the conflict between carbon storage and biodiversity. We also found that trade-offs between timber revenues, carbon storage and biodiversity differed when using different biodiversity indicators (deadwood and species habitat availability). Although both biodiversity indicators showed stronger conflicts with timber revenues than with carbon storage, deadwood was more sensitive to maximizing timber revenues than species habitat availability. This reflects the fact that any increment in the timber extracted from the forest stand is directly linked with a decrease in the availability of deadwood resources.

Our findings are consistent with recent studies showing that either no management (set-aside) or less intensive harvesting regimes benefit both carbon storage and biodiversity (Schwenk *et al.* 2012). The most beneficial management regime for carbon storage and biodiversity was set-aside (no management), which is not an economically viable management regime for private forest owners as it does not provide any timber harvest revenues. Previous studies have shown that no-thinning and longer rotation could be beneficial for both carbon (Liski *et al.* 2001) and biodiversity (Tikkanen *et al.* 2012), and our results also support the importance of these regimes. Overall, it is clear that a multifunctional landscape requires more diversified management than is currently employed in Fennoscandian production landscapes.

It should be noted, however, that our results are influenced by key choices made in the study design like simulation length or choice of discount rate used among others. The 50-year simulation length may underestimate the utility of management regimes that delay final harvest because these regimes are not applicable for the youngest stands. However, the 50-year time window is already quite long compared with the typical forest planning time horizon of 10-20 years (http://www.fao.org/docrep/w8212e/w8212e07.htm). Regarding climate change, the 50-years period is conveniently short to allow us not to take into account the effects of a changing climate as its effects on forest growth will become more evident only towards the end of the 21st century (Kellomäki *et al.* 2008). The choice of an appropriate discount rate when estimating net present values is a controversial and critical issue, especially for studies involving long time horizons. However, around 3-4% discount rate is commonly applied in European countries for evaluating social projects or policies (see Johansson, P.-O., and Kriström 2012 and references therein). Moreover, when trading-off ecological and economic objectives the shapes of the Pareto-frontiers are similar using different discount rates and only change the absolute values (Cheung & Sumaila 2008). The discount rate may, however, affect the optimal combination of management regimes as it changes NPV values of the management regimes (Table S1). For example, with 1% interest rate the proportion of regimes that postpone final harvesting would likely increase (as their NPV rises the least) and the proportion of regimes with no thinnings would decrease (as their NPV rises the most) compared to the optimal solution obtained with 3% interest rate.

Natural disturbances such as wind storms, fires or pest outbreak were not included in our simulations even though disturbances might have a strong influence both on ecosystem services and biodiversity in boreal forests (Thom & Seidl 2015) and they are predicted to increase with climate change (Seidl *et al.* 2014). The risk of disturbances in production forests (like our study area) is minimized because younger and lower density forests are often more resistant to insects and less susceptible to wind damage (Mitchell 2013; O'Hara & Ramage 2013). Furthermore, in Fennoscandia forest fires have been almost totally eliminated and coarse woody debris is removed from production forests after fire or storms through salvage logging. Thus, in our study, disturbances have a relatively small effect on deadwood availability, forest structures and carbon storage in comparison with the effects of management actions.

European policies that aim to enhance the capacity of forests to mitigate climate change include more intensive use of wood-based energy and the extraction of deadwood material from clear-cuts areas and harvested forests (Stupak *et al.* 2007; Felton *et al.* 2016). Our results suggest that intensive management for timber extraction conflicts with climate change mitigation which is in line with Naudts *et al.* (2016) that showed that 250 years of forest management in Europe has accelerated climate warming. Intensified forest-fuel harvesting will reduce the availability of deadwood and might be in conflict with the target of halting the decline of forest biodiversity (Eräjää *et al.* 2010). Biodiversity plays an important role in the delivery of ecosystem services, but the relationship between biodiversity and ecosystem services is a complex and multifaceted one (Cardinale *et al.* 2012; Mace, Norris & Fitter 2012). Further research is needed to incorporate other ecosystem services provided by forests such as collectable goods (e.g., Saastamoinen, Kangas & Aho 2000), water regulation (e.g., Eriksson, Löfgren & Öhman 2011) and explore their relationships with biodiversity (Mori, Lertzman & Gustafsson 2016).

CONCLUSIONS

Our findings offer new insights for sustainable forest management, showing the utility of analytical approaches that combine forest simulation modelling with multiobjective optimization. Our results show that with careful planning it is possible to greatly increase non-timber objectives (especially the biodiversity indicators). Therefore, it is possible to reduce the trade-offs between different objectives by applying diversified forest management planning at the landscape-level. However, we found it difficult to simultaneously maintain high levels of several non-timber and timber objectives. This suggests that we need to give up the all-encompassing objective of very intensive timber production, which is prevailing particularly in Fennoscandian countries. There are several alternative strategies for achieving this. We could spatially segregate the landscape where the target is intensive timber production (land-sparing), we could find a sustainable balance between timber and non-timber objectives (land-sharing) or we could implement mixed strategies that allow for both land-sharing and land-sparing. Recent research has shown that mixed strategies have the greatest potential to achieve all objectives in environmentally and socio-economically heterogeneous regions

(Law *et al.* 2016). Moreover, alternative forest management regimes like continuous cover forestry might help to enhance multifunctionality forestry and resolve conflicts among different objectives.

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Data accessibility

The processed data used for the multiobjective optimization are archived in the University of Jyväskylä Dataverse Network http://dvn.jyu.fi/dvn/dv/Boreal_forest (Triviño *et al.* 2016). The raw data for this study have been archived by the Finnish Forest Center (http://www.metsakeskus.fi/) and the output data from the MOTTI forest growth simulator belongs to the Natural Resources Institute of Finland (https://www.luke.fi/en/).

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Optimizing management to enhance multifunctionality in a boreal forest landscape

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Supporting Information

Fig. S1. Histogram of the distribution of initial stand age.

Appendix S1. Detailed explanation about the forest growth simulator MOTTI, justification for the selection of the time length for the simulation and the combined habitat suitability index.

Appendix S2. Bi-objective optimization: pairwise trade-offs between timber harvest revenues, carbon storage and biodiversity.

Appendix S3. Mathematical formulation of the multiobjective problem.

Table S1. Sensitivity analysis of the net present values of timber harvest revenues to changes in the discount rate.

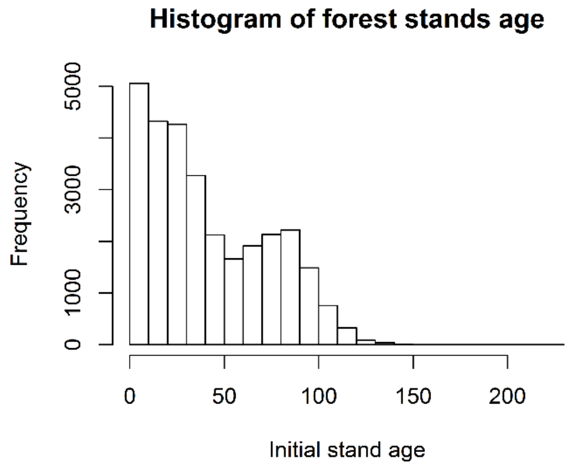

Fig. S1. Histogram showing the distribution of initial stand age in the study area prior to simulations.

Appendix S1. Detailed explanation about the forest growth simulator MOTTI, justification for the selection of the time length for the simulation and the combined habitat suitability index.

MOTTI stand simulator

The stand data used in this study were obtained from a previous study (Mönkkönen *et al.* 2014). The original data was generated using the MOTTI growth simulator developed by the Natural Resources Institute Finland[1]. MOTTI simulator and its forest growth and timber yield equations are described in detail in Hynynen *et al.* (2002, 2005), and the technical outline in Salminen *et al.* (2005). The core of MOTTI comprises specific distance-independent tree-level models for predicting such variables as natural regeneration, tree growth, and mortality, as well as effects of management on tree growth (Salminen *et al.*, 2005). The growth models consist of three functional variable groups describing: (i) growth potential of site (climate and soil), (ii) growth potential of tree (tree dimensions) and (iii) growth reduction caused by between-tree competition (competition indices). The models are based on extensive empirical data from permanent field sites and forest inventory plots (Hökkä, 1997; Hynynen *et al.*, 2002; Matala *et al.*, 2003; Hökkä & Salminen, 2006). Both data sets include measurements from trees older than the usual rotation lengths albeit the data covering growth and natural mortality of very old trees is sparse. Thus, the growth and development of old stands is not predicted as reliably as the growth and development of younger stands. This uncertainty is associated, in particular, to set-aside (SA) and extended rotation (EXT30). MOTTI simulator is best suited for predicting growth and yield under standard silviculture conditions represented in this study by the Business As Usual (BAU) regime.

In MOTTI, retention trees are chosen from the diameter distribution so that they represent different size classes like a natural group of trees would do. Whenever aspen and other deciduous trees are present, they are favoured when selecting retention trees. In reality, deciduous trees are favoured in tree retention but the trees are often left in groups (Mönkkönen *et al.* 2014). The models in MOTTI based on individual tree models are distance-independent and the competition is described using relative size of each tree as well as stand-level characteristics such as basal area. The growth and development of retention trees are predicted with the same models and variables as the other trees and the retention trees have an effect in the simulations e.g., on competition among individual trees and the development of new seedlings. However, some uncertainty concerning the growth and mortality of retention trees remains because the edge effects on retention trees are not specified in MOTTI (Mönkkönen *et al.* 2014). Finally, tree growth, mortality and regeneration in MOTTI are based on up-to-date empirical statistical functions in a static environment. Despite the fact that seed

[1] https://www.luke.fi/en/

dispersal is not included in the forest growth simulator, in our case study this is not a limiting factor as most forest stands are being regenerated by planting new trees.

Time length of the simulation

We ran MOTTI-simulations 50 years into the future. The 50-year time window was selected for several reasons. Firstly, a fifty years period is short enough to not allow a second rotation on a stand that is final harvested at the beginning of the simulation. This is desirable because we wanted to base our simulations on real-world data on the current growing stock of tree. Allowing a second rotation would have resulted in large uncertainties as it would have required a number of assumptions concerning the next rotation. These assumptions involve several decisions regarding silvicultural and forest improvement work, for example, the choice of activities for the preparation of regeneration area and the choice of regeneration method (seedling, planting, natural regeneration). Secondly, it is a compromise between realistic rotation lengths in the region (about 80 years) and the validity of MOTTI-simulations. MOTTI has not been sufficiently tested in forests clearly older than the usual rotation length (e.g., Holopainen *et al.*, 2010), and thus running the simulations far into the future would have resulted in projections that cannot be validated. Finally, this 50 year time horizon is conveniently short to allow us not to take into account the effects of a changing climate as its effects on forest growth will become more evident only towards the end of the 21st century (Kellomäki *et al.*, 2008).

It should be noted that the 50-year simulation length likely underestimates the importance of management regimes that delay final harvest (i.e. extended rotation by 10 or 30 years) because these regimes are not applicable for the youngest stands, i.e. no extension can take place within the 50-year time window. However, our data included over 10,000 stands for which all the management regimes can be applied because their initial stand age is above 50 years old. Hence, most likely the 50-year time horizon does not affect the results considerably. Moreover, the 50-year time window is already quite long compared with the typical forest planning time horizon of 10-20 years[2].

Combined habitat suitability index

The combined habitat suitability index (HSI) was designed to reflect conservation value as truthfully as possible. As defined here, it attains a high value if the stand is at least moderately suitable for all of the focal species or highly suitable for at least one of the species. For example, it is possible that under one forest management regime a stand is very suitable for one species and very poor for the rest, and under another regime quite poor for all species. In this case e.g., the sum of the individual indices may be higher for the latter outcome than the former, but the combined index values the

[2] http://www.fao.org/docrep/w8212e/w8212e07.htm

former outcome more highly than the latter. This is desirable because we selected the six focal species so that a wide spectrum of habitat associations and societal values (game, indicator and threatened species) were included. If a stand is of high quality for any of the species, it has conservation value.

As the six focal species have different habitat requirements and as the studied stands are variable in their characteristics, varying amounts of highly suitable habitat can be provided within the landscape to the different species. The six species may thus contribute to the combined HSI to differing degrees. However, all of the focal species have also been shown to suffer losses in quality of habitat due to timber-focused management, with none of them being particularly compatible with intensive timber production (Mönkkönen *et al.* 2014). We verified that the value of the combined HSI at the level of the entire landscape was not driven by a single species. We checked the correlations between the combined HSI and the individual HSI under each one of the seven management regimes and found that the correlation values were quite similar and quite weak for all the species (Spearman's correlations, *r*=0.1-07).

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Appendix S2. Bi-objective optimization: pairwise trade-offs between timber harvest revenues, carbon storage and biodiversity.

In the set of Pareto optimal plans, we found that trade-offs between timber NPV and biodiversity were stronger than between carbon storage and biodiversity. Maximizing deadwood resources caused a 55% reduction in NPV but only 6 % reduction in carbon storage (Fig. S2A vs S2B). Corresponding values for the other biodiversity indicator were 43% reduction in NPV and 11% reduction in carbon storage (Fig. S2D vs S2E). However, the slopes of the curves of the trade-offs between NPV and biodiversity were quite flat at low levels of biodiversity, meaning that the first increments in the biodiversity levels were inexpensive. The trade-off between NPV and carbon storage was quite strong as the slope of the curve was steep and maximizing carbon resulted in the highest (64%) reduction in NPV.

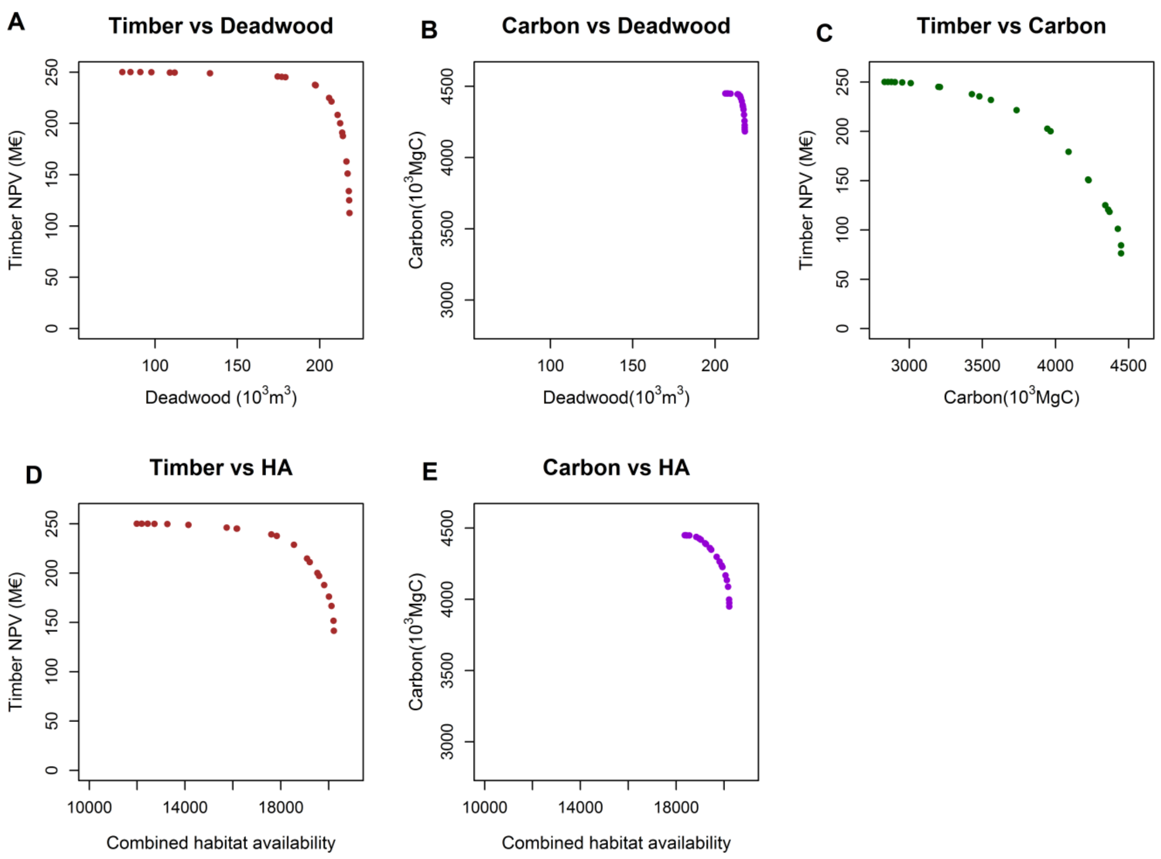

Fig. S2. Bi-objective optimization results: curves representing the outcomes of the Pareto optimal plans describing the pairwise trade-offs between timber harvest revenues, carbon storage and the two biodiversity indicators (diversity of deadwood and combined probability of habitat suitability index of 6 vertebrate species) at the landscape level. Note that Fig. S2C is adapted from Fig. 5 in Triviño *et al.*, 2015.

Appendix S3. Mathematical formulation of the multiobjective problem.

To reveal the relationships among the objectives (timber harvest revenues, carbon storage and biodiversity), we explored the potential of the landscape to provide them simultaneously by solving a multiobjective optimization problem:

$$\text{maximize } (f_1(x), \ldots, f_n(x))$$
$$\text{subject to } x \in X,$$

where $f_1(x), \ldots, f_n(x)$ are objective functions and X is the set of alternative management regimes. Here, the objective functions are for timber harvest revenues (NPV), carbon storage and biodiversity. The value of each objective function depends on x, i.e. the management regime applied.

Let $s = 1,2,\ldots,m$ be the index of forest stands and $r = 1,2,\ldots,n$ be the index of management regimes. The decision variables are the following binary variables:

$$x_{sr} = \begin{cases} 1, \text{ if the } r\text{-th management regime is selected for the } s\text{-th stand;} \\ 0 \text{ otherwise.} \end{cases}$$

The set of feasible solutions is defined by:

$$X = \left\{ x = (x_{sr})_{m\times n} \in \{0,1\}^{m\times n} \colon \sum_{r=1}^{n} x_{sr} = 1 \text{ for each } s = 1, \ldots, m \right\}.$$

Thus, each feasible solution is a management plan where for each forest stand, one of management regimes is selected.

Any of three objective functions $f_i(x)$ I = 1,2,3, is defined by the formula:

$$f_i(x) = \sum_{s=1}^{m} \sum_{r=1}^{n} c_{sr}^{(i)} x_{sr},$$

where coefficient $c_{sr}^{(i)}$ is the contribution of the s-th stand to the value of i-th objective in the case where the r-th management regime is selected. In other words, for each forest stand s and each management regime r, the coefficients describe the following outcomes of managing stand s with regime r:

- $c_{sr}^{(1)}$ – timber harvest revenues from the stand;
- $c_{sr}^{(2)}$ – amount of carbon stored by the stand;
- $c_{sr}^{(3)}$ – the indicator of stand's contribution to the biodiversity of the landscape (volume of deadwood or the combined habitat availability).

Table S1. Sensitivity analysis of the net present values of timber harvest revenues to changes in the discount rate. We carried out a sensitivity analysis for two alternative discount rates: very low (1%) and very high (5%). The median increase and decrease has been calculated comparing the new values (1 and 5%) with the reference discount rate (3%) on the basis of individual forest stand and for each management regime. For example, if we apply a 1% discount rate we will obtain a 92% higher NPV (on average) than when we apply a 3% discount rate. "SD" refers to the standard deviation and was used as measure of the amount of variation or dispersion in the values. The acronyms of the management regimes are the same as in Table 1.

Forest regime	1% rate: median increase (± SD)	5% rate: median decrease (± SD)
BAU	92.5% (± 76.4)	-53.3% (± 43.5)
EXT10	33.0% (± 50.7)	-17.6% (± 28.6)
EXT30	79.6% (± 71.8)	-43.6% (± 21.0)
GTR30	94.1% (± 79.7)	-45.2% (± 28.2)
NTLR	99.9% (± 201.9)	-49.2% (± 72.9)
NTSR	166.6% (± 203.4)	-61.8% (± 72.5)