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Managing a boreal forest landscape for providing timber, storing and sequestering carbon

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ABSTRACT

Human well-being highly depends on ecosystem services and this dependence is expected to increase in the future with increasing population and economic growth. Studies that investigate trade-offs between ecosystem services are urgently needed for informing policy-makers. We examine the trade-offs between a provisioning (revenues from timber selling) and regulating (carbon storage and sequestration) ecosystem services among seven alternative forest management regimes in a large boreal forest production landscape. First, we estimate the potential of the landscape to produce harvest revenues and store/sequester carbon across a 50-year time period. Then, we identify conflicts between harvest revenues and carbon storage and sequestration. Finally, we apply multiobjective optimization to find optimal combinations of forest management regimes that maximize harvest revenues and carbon storage/sequestration. Our results show that no management regime alone is able to either maximize harvest revenues or carbon services and that a combination of different regimes is needed. We also show that with a relatively little economic investment (5% decrease in harvest revenues), a substantial increase in carbon services could be attained (9% for carbon storage; 15–23% for carbon sequestration). We conclude that it is possible to achieve win–win situations applying diversified forest management planning at a landscape level.

1. Introduction

Over the past centuries, humans have had a tremendous impact on their environment, mostly to meet rapidly growing demands for resources along with economic development (Vitousek et al., 1997). These demands have caused severe ecosystem degradation and biodiversity loss (e.g., MEA, 2005; Rapport et al., 1998). Ecosystem services represent direct and indirect benefits that people obtain from ecosystems (MEA, 2005) and our dependence on their consumption is expected to increase in the future with an increasing population and economic growth (Guo et al., 2010). Therefore, studies about trade-offs between ecosystem services are urgently needed to inform decision-makers and managers of natural resources to take appropriate management actions. As a result, international, continental and national policies have been formulated such as the Intergovernmental Platform on Biodiversity and Ecosystem Services, the European Union Biodiversity Strategy for 2020 and the Finnish national strategy (www.ipbes.net, European Commission, 2010; Finnish Government Resolution, 2012).

Many crucial ecosystem services are provided by forests (Gamfeldt et al., 2013; García-Nieto et al., 2013; Vanhanen et al., 2012). The boreal biome represents approximately one-third of all remaining global forests (Bradshaw et al., 2009; Hansen et al., 2010) and constitutes approximately 45% of the world's stock of growing timber (Vanhanen et al., 2012). Moreover, boreal forests store about one third of the global terrestrial carbon in forests (Pan et al., 2011). Therefore, the absence of boreal forests from global policy agendas on climate change mitigation (e.g., REDD+ program) represents an important

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missed opportunity that should be corrected (Moen et al., 2014). Most commercial forests worldwide have been intensively managed for maximizing the provision of timber, while maintaining biodiversity and other ecosystem services such as water and climate regulation, soil retention and recreational values have received less attention (Gerasimov et al., 2012; Guariguata et al., 2012). Management based on a single ecosystem service is potentially problematic, as it might undermine the long-term provision of other ecosystem services (Balvanera et al., 2014; Rodríguez et al., 2006). For example, in northern Europe, intensive forest management for timber production might reduce water quality (Eriksson et al., 2011). Moreover, intensive timber extraction has caused profound ecological changes in forests like simplification of stand structure (e.g., homogenization of tree's age and composition), reduction of dead wood, altered disturbance dynamics (e.g., fire suppression) and the loss and fragmentation of old growth forests (Brumelis et al., 2011; Hanski, 2005; Siitonen, 2001). Thus, the biggest challenge in forest management is to simultaneously maintain the provision of timber, biodiversity and other ecosystem services (e.g., de Groot et al., 2010).

Forests help to regulate climate and, more specifically, mitigate climate change by sequestering CO_2 from the atmosphere and storing it in different biomass pools (e.g., Powers et al., 2013). *Carbon storage* represents the carbon stock (the amount of carbon fixed in the system at a given time; size of storage pools) whereas *carbon sequestration* represents the carbon flux (the amount of carbon exchange between atmosphere and forests between two points in time) (Powers et al., 2013). Even though values of *carbon storage* and *sequestration* will tend to coincide in the long term because all carbon fixed through photosynthesis will eventually be released back to the atmosphere (Liski et al., 2001), they represent different aspects of climate regulation when considering forest management for a short period of time. Trees sequester carbon as they grow, so a critical aspect in carbon sequestration is the rate of tree growth (van Kooten et al., 1995). Usually fast-growing tree species sequester more carbon at the beginning of their lives, whereas carbon sequestration rates for slow-growing trees will be higher later on (Nghiem, 2014). Since about 12.5% of anthropogenic carbon emissions from 1990 to 2010 are due to land-use change and deforestation (Houghton et al., 2012) sustainable forest management can play an important role in climate change mitigation. Forest management practices can greatly affect whether forests act as net carbon sources or sinks (e.g., Birdsey et al., 2006).

Finland is the most forested country in Europe and in the boreal zone (UNEP FAO and UNFF, 2009) with around 86% of its territory covered by forests and most of Finland's forests are under commercial management (Finnish Forest Research Institute, 2011). There is a long history of forestry in Finland and this expertise can be seen as an opportunity to develop and implement management practices that promote ecosystem services besides timber production (Moen et al., 2014). For example, the frequency and intensity of thinning play very important roles in timber production and carbon sequestration (Cao et al., 2010; Hynynen et al., 2005) as well as in berry production (Miina et al., 2010). Regulating the rotation length is also an effective way to increase forest carbon sequestration (Hynynen et al., 2005; Liski et al., 2001) and berry production (Miina et al., 2010). Therefore, investigating the effects of different land-use and management decisions on different ecosystem services is vitally important.

In this study, we examined trade-offs between a provisioning ecosystem service (timber) and regulating ecosystem service (carbon storage/sequestration) across a large boreal forest production landscape in central Finland. Using market prices, we estimated the net present value of harvest revenues to measure the economic value of timber production as a provisioning service. However, we used the biophysical amount of carbon to measure regulating services, as the carbon markets are still not established for boreal forests. Our main aim is to identify forest management regimes which improve simultaneously both ecosystem services studied. We go beyond previous studies and incorporate forest dynamics by simulating forest growth in a landscape with about 30,000 stands during 50 years to obtain future forest growth and yield projections. Forest stands are simulated considering seven alternative management regimes ranging from the recommended management (business as usual) to setting aside entire forests stands. The effects of several forest management regimes on multiple ecosystem services in a dynamic context have been rarely assessed (an exception to this is given in e.g., Pukkala et al., 2011). We also apply multiobjective optimization for analysing trade-offs between these different objectives (Miettinen, 1999). The explicit analyses of trade-offs can identify where the current management actions are inefficient to provide multiple goods or services, such as timber production or carbon storage. These analyses can also identify situations where carbon storage can be increased without any, or with only minimal, reductions in the production of timber, or vice versa. Specifically, we address the following questions: (i) What is the potential of the forest landscape and the optimal combinations of management regimes to simultaneously produce economic revenues and regulate climate? (ii) Is there a difference between the two carbon measures regarding to their trade-offs with timber production? This is an interesting question as carbon storage and sequestration reflect different aspects of climate regulation.

2. Material and methods

2.1. Study area

Our study area is a typical boreal production forest landscape located in Central Finland (62°14′N, 25°43′E) (Fig. 1). The total area is 687 km^2 and forest on mineral soils covers 55%, peat lands 13%, lakes 16% and farmland settlement some 15% of the area. Scots pine (*Pinus sylvestris*), Norway spruce (*Picea abies*), birch (*Betula pendula* and *Betula pubescens*) and mixed stands dominate the forest consisting of 29,706 stands of an average size of 1.45 ha (stand size ranges between 0.06 and 17.5 ha). Past forest management practices have resulted in a bimodal age structure of forest stands with a large proportion being less than 40 years of age, and another large part being between 70 and 90 years old (see the complete distribution of stand age in Fig. S1 in Supplementary material).

2.2. Forest data, management regimes and forest growth simulations

We extracted data for forest growth modelling from the data administered by the Finnish Forest Centre, a governmental administrative organization for legal control and enhancement of forestry in private land. The data are organized as forest stands that are basic units for forest inventories. We considered seven alternative management regimes for each stand (see Table 1): (1) *BAU* (Business as usual): in this management regime thinning and final harvest are conducted according to current recommendations (Yrjölä, 2002) which results in more or less homogeneous monoculture of trees; (2) *SA* (Set aside) represents a permanent conservation strategy; (3) *EXT10* (Extended rotation by ten years): postponing final harvest produces some additional mortality (more dead wood) and larger and older trees. This strategy represents a short-term conservation strategy; (4) *EXT30* (Extended rotation by thirty years) represents a long-term conservation strategy; (5) *GTR30* (Green tree retention) represents a conservation oriented management regime that attempt to mimic and restore

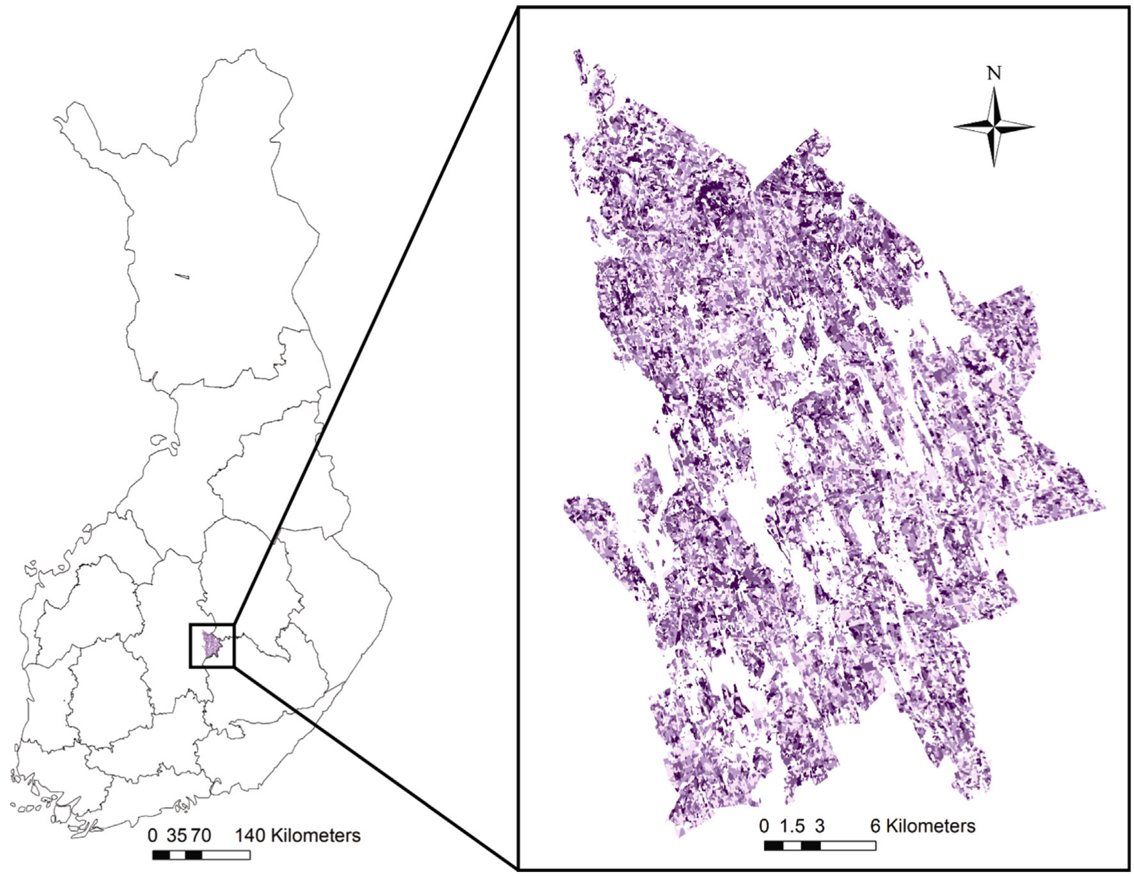

Fig. 1. Map of the location of the study area in Finland.

Table 1
Management regimes applied on the forest stands (adapted from Mönkkönen et al., 2014).

Management regime	Acronym	Description
Business as usual	BAU	Recommended management: 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 thinning (final harvest threshold values as in BAU)	NTLR	Otherwise BAU regime but no thinning; therefore trees grow more slowly and final harvest is delayed; average rotation length 86 years
No thinning (minimum final harvest threshold values)	NTSR	Otherwise BAU regime but no thinning; final harvest adjusted so that rotation does not prolong: average rotation length 77 years

natural disturbances regimes (Vanha-Majamaa and Jalonen, 2001); (6) *NTLR* (No thinnings with long rotation): avoiding thinning results in a slower tree growth, as it takes longer to reach the recommended tree diameter (the middle of recommended threshold value range) for final harvest. It is expected that the harvest revenues of this management regime are smaller than for BAU due to lost thinning revenues and longer rotations; (7) *NTSR* (No thinnings with short rotation) represents a management regime where thinnings are not allowed and the final harvest is set to take place approximately at the same time as in BAU (for further details see Mönkkönen et al., 2014).

We ran forest growth simulations for 50 years in 5 years' intervals, which resulted in 11 time steps. The development of forest stands under different management regimes was projected using 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., Ahtikoski et al., 2011; Hynynen et al., 2005; Kojola et al., 2012). The models used in MOTTI are based on empirical data from forests managed mainly according to prevailing regulations (Business as usual). Thus applying MOTTI for other management regimes might require extrapolation and causes some uncertainty in model predictions (for further details see Mönkkönen et al., 2014). The core of MOTTI comprises specific distance-independent tree-level models for predicting variables such as natural regeneration, tree growth, and mortality, as well as effects of management on tree growth (Salminen et al., 2005).

2.3. Net present value of harvest revenues

In order to transform the extracted timber into an economic value, we calculated the net present value (NPV) of harvest revenues for each management regime and forest stand (see Mönkkönen et al., 2014 for details). In these calculations, we used stumpage prices for eight timber assortments (pulp wood and saw logs for each tree species: Scots pine, Norway spruce and two birch species) and unit costs of five different silvicultural work components including natural regeneration, seedling, planting, tending of seeding stands, and cleaning of sapling stands (Finnish Forest Research Institute, 2012). In addition, as previously said, we used a 50-year planning horizon divided into ten 5-year periods and applied a 3% real interest rate in discounting the revenues and costs occurring at different time periods.

2.4. Carbon measurements

Even though carbon storage and sequestration terms are highly interrelated and sometimes climate regulation is measured using only carbon sequestration (e.g., Nelson et al., 2009), these two terms describe different aspects of climate regulation. Carbon storage (CStor) is a measure of the ecosystem's capacity to retain carbon (prevent further release of stored carbon) while carbon sequestration relates to mitigating anthropogenic carbon emissions (transferring atmospheric CO_2 into long-lived pools). We adopt terminology from Powers et al. (2013), where carbon storage refers to the size of the carbon pool at a certain point in time and sequestration to the rate of annual transfer of carbon between the atmosphere and forests. Different types of forests can provide different services as old forests store large amounts of carbon (Luyssaert et al., 2008) while young fast-growing forests may have higher annual carbon sequestration rates (Jandl et al., 2007).

There is some controversy about whether wood products (extracted timber) should be considered or not when calculating the amount of sequestered carbon. Some argue that the potential of the forest sector to sequester carbon becomes underestimated if these products are not taken into account (Karjalainen et al., 1994). For that reason, we considered two measures of carbon sequestration: one that includes the carbon in harvested timber (carbon sequestered [CSeq]) and another that excludes the carbon in harvested timber (carbon sequestered non-extracted [CSeqNoExt]).

For calculating the three carbon measurements (CStor, CSeq and CSeqNoExt), we considered the four most common tree species in boreal forests: Scots pine (*P. sylvestris*), Norway spruce (*P. abies*) and two birches (*B. pendula* and *B. pubescens*) and the carbon pools most affected by forest management regimes: (i) living wood; (ii) dead wood; (iii) harvested timber; (iv) residual carbon left after thinning or final harvest. *Carbon storage* (CStor) was calculated for each stand as the average amount of carbon biomass across the 11 time steps. *Carbon sequestration* (CSeq) was calculated for each stand as the sum of changes in carbon stock across all time steps and *carbon sequestered non-extracted* (CSeqNoExt) was calculated in the same way as carbon sequestration but excluding harvesting timber from the estimates (for further information about carbon calculations see Appendix A). In this study we did not take into account the carbon biomass of understory and litter as they represent a small fraction of the total carbon in most forests (Brown, 2002). Because we did not have data available for estimating carbon biomass in soils, it was not considered in this study despite the high importance of soil carbon (Liski et al., 2006). The review of Nave et al. (2010) showed a significant decrease in soil carbon following harvesting. However, carbon losses could be largely avoided by reducing physical disturbance to the soil profile during site preparation.

2.5. Identifying the best and worst forest stands for providing harvest revenues and carbon

To reveal the maximum capacity of each individual stand to produce timber and store/sequester carbon, prior to optimization, we identified the management regime that provides the highest value of timber and carbon across the seven management regimes. It is likely that the regime which provides the highest value of carbon is different from the regime which provides the highest value of timber, but it is also possible that the same management regime provides the highest value for both ecosystem services. To explore conflicts between the maximum provision of harvest revenues (NPV) and the three measurements of carbon, we identified stands which were simultaneously good for providing harvest revenues and carbon. We classified stands above the third quartile in the range of values of NPV and carbon measurements as the *best* and stands below the first quartile of NPV and carbon measurements as the *worst*. The stands classified as the *best* were the ones that provided the highest value for both ecosystem services and where forest owners could obtain more benefits, while the *worst* stands represented forests where the capacity for providing both services was low. We additionally plotted the values of NPV and carbon measurements against each other for each individual management option. Then, we identified how initial (at year 0) forest stand characteristics (age, proportion of pine biomass, proportion of spruce biomass and proportion of birch biomass) were associated with the *best* and the *worst* forest stands (using boxplots and Mann–Whitney test to analyse whether the stand characteristics differed between the *best* and the *worst* stands).

To shed more light on the conflicts between harvest revenues and the three carbon measurements we identified the forest stands for which the management regime that provided the highest value of timber and each one of the carbon measurements matched (*matching*) or did not match (*not matching*). In addition, we carried out the same analyses but excluding the set-aside management option because it does not produce any harvest revenues. We also explored how the initial forest stand characteristics were associated with the *matching* and the *not matching* forest stands for these additional analyses excluding set-aside management option. Spatial representation of forest stands was carried out within the Geographical Information System (GIS) software ArcGIS 10.1 (ESRI, 2011) and all the statistical analyses were performed using R version 3.0.2 (R Development Core Team, 2013).

2.6. Multiobjective optimization analyses: Optimal combination of management regimes

To explore the maximum capacity of the landscape to produce harvest revenues and each one of the three carbon measurements, we produced *management plans* (a combination of management regimes assigned to all forest stands) that maximized harvest revenue (NPV) from timber production and the carbon measurement by solving the following bi-objective optimization problem:

$$\text{maximize } (f_1(x), f_2(x))$$

$$\text{subject to } x \in X,$$

where X is the set of alternative management regimes, $f_1(x)$ is NPV and $f_2(x)$ is the objective function for the carbon measurement over the 50-year planning period resulted from applying management plan $x \in X$.

Using multiobjective optimization we maximized both objective functions simultaneously to determine *management plans* that are Pareto optimal instead of selecting the single best management regime based on only one objective. (Pareto optimal plans involve different trade-offs among the objectives and none of the objectives can be improved without impairing at least one of the others. All Pareto optimal plans form a Pareto optimal set. For further details, see e.g., Miettinen, 1999). This enables analysing trade-offs between revenues from timber production and carbon measurements. The calculations were carried out using IBM ILOG CPLEX optimizer (http://www-01.ibm.com/software/commerce/optimization/cplex-optimizer/). 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).

To illustrate Pareto optimal combinations of management regimes that maximize carbon for different fixed levels of harvest revenues, we created graphs for each carbon measurement to represent how the optimal allocation of management regimes for forest stands evolves with increased levels of carbon (and decreased economic returns). In multiobjective optimization, this method is called the ε-constraint method (Miettinen, 1999). Then we focused on a specific situation when the society is willing to give up 5% of the maximum economic revenue for favouring climate change mitigation (i.e., 95% level of maximum economic returns). The 5% level was selected because it roughly corresponds with the political decisions already taken in Finland regarding biodiversity conservation through the METSO II program (Finnish Forest Research Institute, 2011). Also because forest certification rules in Sweden require that 5% of the forest area should be permanently set aside from forestry to conserve biodiversity (Forest Stewardship Council, 2010). We may assume that a similar level of investment could be applied for climate change mitigation.

3. Results

3.1. Identifying the best and worst forest stands for providing harvest revenues and carbon

The forest stands that provided the highest value of harvest revenues and carbon differed depending on which carbon service was measured (Fig. 2). The stands that provided the highest value of harvest revenues were almost the same ones as the stands that provided the highest value of carbon storage (Spearman's correlation, $\rho_{NPV\text{-}CStor}=0.95$), however there was not much coincidence when we explored the relationship between harvest revenues and the two carbon sequestration measurements (Spearman's correlations, $\rho_{NPV\text{-}CSeq}=0.45$ and $\rho_{NPV\text{-}CSeqNoExt}=0.41$) (Fig. 2A). This resulted in a higher percentage of the forest stands classified as the *best* (22%) and as the *worst* (20%) in carbon storage than in carbon sequestration measurements: *best* (% $\text{stands}_{\text{CSeq}}=11\%$; % $\text{stands}_{\text{CSeqNoExt}}=10\%$) and *worst* (% $\text{stands}_{\text{CSeq}}=11\%$; % $\text{stands}_{\text{CSeqNoExt}}=10\%$) (Fig. 2B). The pairwise correlations among harvest revenues and carbon measurements were higher when examining the highest value across all management options (Fig. 2A) than when exploring the correlations in each of the seven forest management regimes individually (Fig. S2). In the latter case, the correlations diverged considerably (Spearman's correlations between harvest revenues and each of the carbon measurements: carbon storage [$\rho_{NPV\text{-}CStor}=0.56-0.81$], total carbon sequestered [$\rho_{NPV\text{-}CSeq}=-0.37--0.03$], and carbon sequestered excl. extracted [$\rho_{NPV\text{-}CSeqNoExt}=-0.55--0.21$], respectively) (Fig. S2). The reason for these low correlation values is that most of the times the forest management regime that maximized NPV was different from the management regime that maximized carbon (see Table S1).

The *best* forest stands for providing ecosystem services differed from the *worst* stands in terms of median age and proportion of timber volume of the different tree species (Mann–Whitney test, all $p<0.001$). The *best* stands were more mature and had a higher

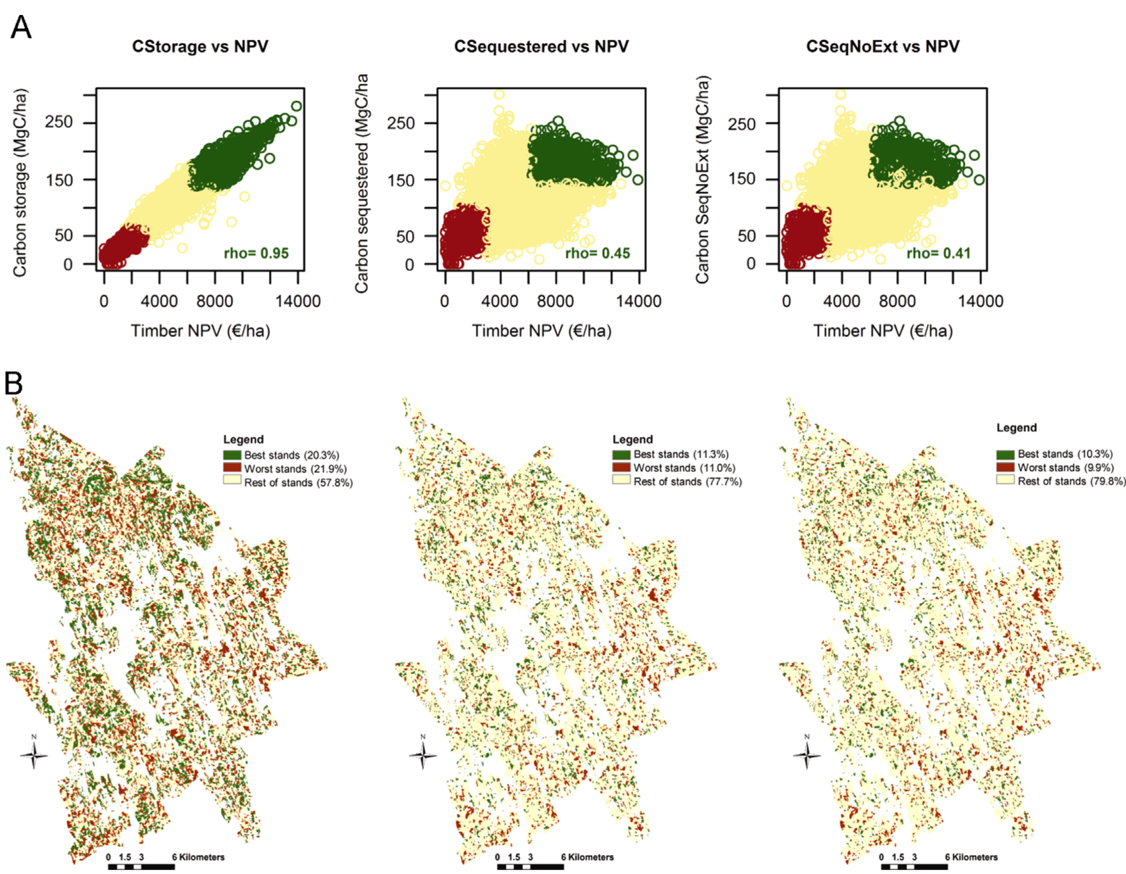

Fig. 2. Scatterplots and spatial patterns for each carbon measurements. The scatterplots (A) indicate the forest stands for which the highest values across all management options for both harvest revenues and each one of the carbon measurements were obtained (*best* stands, dark green colour) and the forest stands for which the lowest values for both harvest revenues and each one of the carbon measurements were obtained (*worst* stands, dark red colour). Moreover, the Spearman's correlation results (rho values) indicate the level of agreement between the harvest revenues and the three different carbon measurements. The maps (B) represent the location of the *best*, *worst* and the rest of the forest stands (yellow colour) in the study area. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

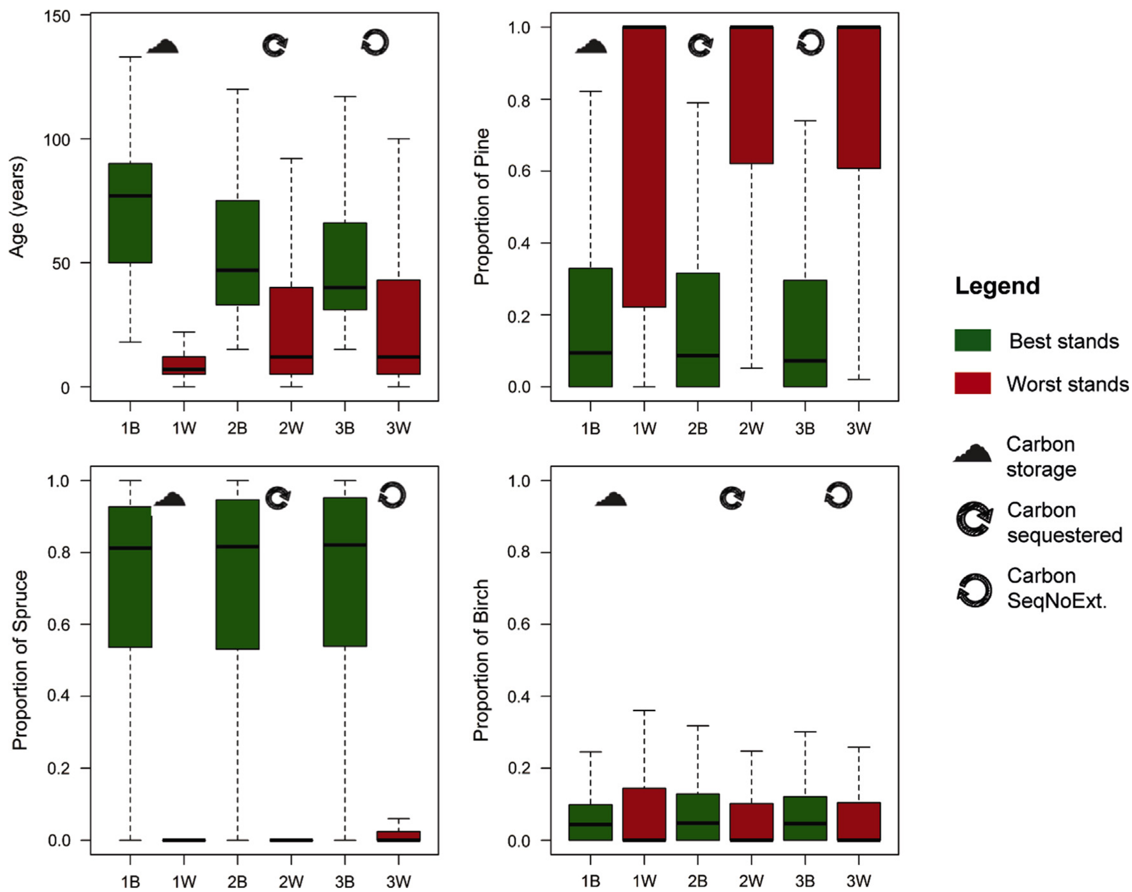

Fig. 3. Boxplots comparing the forest stand characteristics (age and proportion of biomass for the three main tree species) between the *best* and the *worst* stands for the three carbon measurements (where **B** refers to the *best* stands and **W** to the *worst* stands; **1** refers to values for NPV and carbon storage; **2** refers to values for NPV and carbon sequestered and **3** refers to values for NPV and carbon sequestered non extracted).

proportion of spruce volume than the *worst* stands at the beginning of the time period (at year 0). The *worst* stands had a higher proportion of pine volume than the *best* stands and the birch volume did not have a clear effect on the capacity of the stands to provide ecosystem services (Fig. 3).

Regarding the *best* and the *worst* stands for providing harvest revenues and carbon services, the management regime that, most of the times, was identified to provide the highest value for harvest revenues (NPV) was business as usual; whereas the management regime that, generally, provided the highest value for the carbon services was set-aside. This indicated a conflict because the same management regime could not provide the highest value for both objectives. Thus, we explored further the conflicts by identifying the forest stands for which the management regime that provided the highest value of NPV was the same (*matching*) as for carbon measurements and the forest stands for which the management regime did not coincide (*not matching*) (Fig. 4). Stands with matching management regime represent a win–win case. Most of the *matching* stands were also classified as the *worst* stands for maximizing carbon services and NPV (70% for CStor; 32% for CSeq and 41% for CSeqNoExt) (Table S1) but this pattern was not found when excluding the set-aside management regime (see Fig. S3). Across all management regimes, win–win situations could be found on stands with a relatively low capacity for timber revenues but a high capacity for carbon sequestration (Fig. 4). When excluding the set-aside regime, win–win situations were more scattered across the full gradient of timber revenues (Fig. S3), indicating that it is possible to find stands where a single management regime will provide the highest value both for timber and carbon. At the beginning of the time period (at year 0), *matching* stands tended to be younger and contained a lower proportion of spruce out of the total timber volume than in *not matching* stands (Fig. S4).

3.2. Optimization results: Trade-offs between harvest revenues and carbon

In the set of Pareto optimal plans, trade-offs between the harvest revenues and the carbon services showed a nonlinear interdependence when different plans were connected to form curves (Fig. 5). The slopes of the curves were quite flat for small values of carbon, meaning that the first increments of carbon storage or sequestration were inexpensive. Maximizing the total amount of carbon sequestered and carbon sequestered without considering the extracted timber resulted in large NPV losses, but it was even more expensive to maximize the total amount of carbon storage as the curve was steeper (see Table 2 and Fig. 5). We also showed that BAU, the currently applied management regime, was not efficient because when it was applied consistently the outcomes were below the potential harvest production (see three points in Fig. 5).

3.3. Optimal combinations of forest management regimes

When a single forest management regime was applied consistently, setting aside stands was the most beneficial strategy for the three carbon measurements, followed by extended rotation (30 years) for carbon storage and by no thinnings (long rotation) for carbon sequestration (Table 3). By contrast, the business as usual, if applied consistently, provided the lowest carbon storage values and extended rotation 10 years was the least beneficial regime for

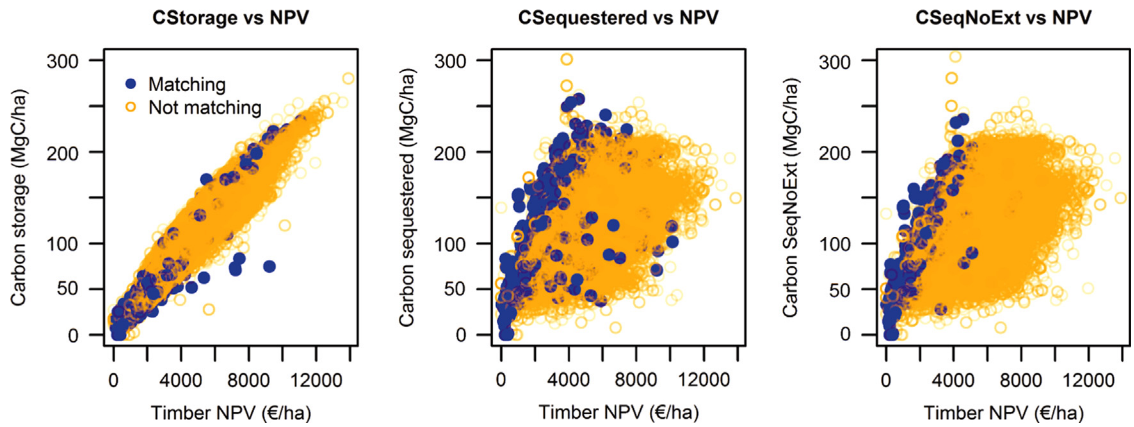

Fig. 4. Scatterplots that indicate the forest stands for which the management regime to maximize timber and each one of the carbon measurements is the same (*matching*, blue colour) or is not the same (*not matching*, orange colour). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

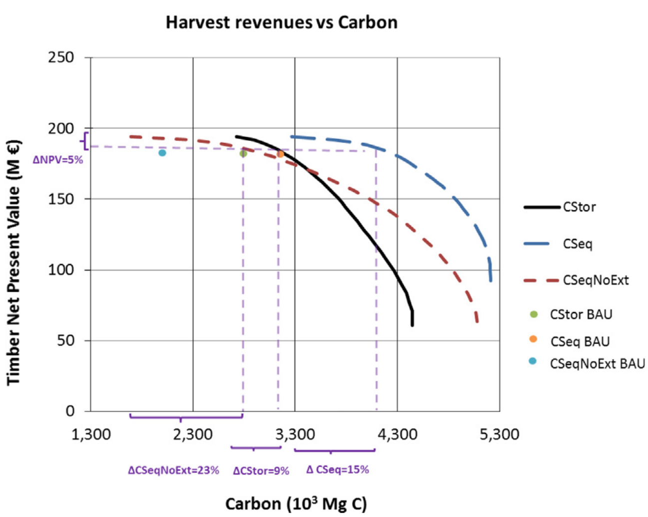

Fig. 5. Curves representing Pareto optimal plans describing the trade-offs between carbon services (carbon storage and carbon sequestration; Mg of carbon, averaged across every 5 years) and harvest revenues (net present value) for the three different carbon measurements. The reference line for a change of 5% in the NPV is included (dashed and light violet colour line) and the changes for each carbon measurement (when the dashed line intercepts with each one of the three carbon measurements). The three points show where exclusive application of the current management regime (BAU=Business as usual) locates. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2
Potential of the landscape to provide harvest revenues (NPV), carbon services examined using three carbon measurements (average MgC per 5 years), and costs related to carbon services. *Carbon Min.* and *Carbon Max.* represent the minimum and the maximum amount of carbon among all Pareto optimal plans. *Abs. NPV diff.* is the absolute difference in NPV between the minimum and the maximum carbon values in the Pareto optimal sets (maximum NPV is 194 M€ in all cases), i.e. the absolute cost of maximizing carbon storage/sequestration. Relative carbon and NPV ranges illustrate the potential (in percentages) that exists to decrease carbon storage/sequestration or NPV.

Carbon measurement	Carbon min. (10^3 MgC)	Carbon max. (10^3 MgC)	Relative carbon range (%)	Abs. NPV diff. (M€)	Relative NPV range (%)
Carbon storage	2730	4449	39	132	69
Carbon sequestered	3266	5214	37	105	54
Carbon SeqNoExt	1697	5078	67	130	67

the two carbon sequestration measurements (Table 3). One can summarize that there was no single management regime that, if applied consistently, maximized the carbon values (Table 3).

The combination of management regimes that maximized harvest revenues was business as usual (60% of the stands), no thinnings (32%) and green tree retention (8%) regimes (Table 4). This combination was used as a reference solution. The changes in the proportion of alternative management regimes with increasing values of carbon in the Pareto optimal set were different for the three carbon measurements (Fig. S5). For increased levels of carbon storage, there was an increment of the application of extended rotation regimes (at the beginning a high increment of EXT10 and then of EXT30). Increasing both measurements of carbon sequestration would require more no-thinning regimes, especially NTSR and GTR30. Set aside should increasingly be applied when targeting high in all carbon values.

If the society is willing to invest 5% of harvest revenues for carbon related ecosystem services, an increase of around 9% in the levels of carbon storage, 15% in carbon sequestration and 23% in carbon sequestration excluding extracted timber can be achieved (Fig. 5). The required changes in units in the management regimes differed among the three carbon measurements (Table 4). For example, to achieve the 9% increase in carbon storage it is required, in the optimal case, to make an 11% reduction in the share of BAU regime and a 10% reduction in no thinning short rotation. These regimes were replaced by applying more extended rotations and no-thinning with long rotation. Likewise, to increase carbon sequestration required a considerable reduction of the BAU regime, and an increase of the two no-thinning and the green-tree retention regimes (Table 4 and Fig. S5).

4. Discussion

In this study we identify optimal combinations of seven forest management regimes in a large boreal landscape with about 30,000 stands for a 50-year time period. Our analyses show that there are forest stands where it is possible to (i) greatly increase the levels of carbon (especially of carbon sequestration) with little economic investment and (ii) maximize both the provisioning (timber production) and regulating (carbon storage/sequestration) services. This requires adequate optimization methods and forest management planning.

The trade-offs between timber and carbon differed when looking at carbon storage or carbon sequestration. We found a strong correlation between the stands that provide the highest

Table 3
Net present value (NPV) and absolute carbon values (MgC) for alternative management regimes if applied consistently across all the stands. For the carbon measurements also the percentage of the maximum carbon (Table 2) is given in brackets. The most beneficial exclusive strategy for different carbon measurements is given in bold.

	BAU	SA	EXT10	EXT30	GTR30	NTSR	NTLR
NPV if applied consistently (M€)	187	0	167	159	182	170	159
Carbon measurements							
Carbon storage, 10^3 MgC	2776 (62.4%)	**4431 (99.6%)**	3030 (68.1%)	3751 (84.3%)	2867 (64.4%)	2880 (64.7%)	3227 (72.5%)
Carbon sequestered, 10^3 MgC	3143 (60.3%)	**5019 (96.3%)**	3063 (58.7%)	3664 (70.3%)	3459 (66.3%)	3592 (68.8%)	3971 (76.2%)
Carbon SeqNoExt., 10^3 MgC	1370 (27.0%)	**5019 (98.8%)**	1345 (26.5%)	2110 (41.6%)	1756 (34.6%)	2267 (44.6%)	2884 (56.8%)

Table 4
Changes in units in the share of different management practices in the Pareto optimal set at the 5% level of carbon cost (95% of the maximum NPV) for the different carbon measurements. The first row gives the reference solution, i.e. the share when the target is to maximize NPV. The rest of the rows give the changes from the reference solution. For example, for carbon storage when there is a reduction of 5% of carbon cost, the management regime BAU is reduced by 11% but there is an increase of 10% in the application of EXT10.

	Management regime						
	BAU	SA	EXT10	EXT30	GTR30	NTSR	NTLR
	59.5	0	0.3	0	8.4	30	1.7
Carbon storage	−11.1	0.0	10.0	5.1	−0.7	−10.4	7.1
Carbon sequestered	−25.6	0.0	5.6	1.2	7.7	3.8	7.2
Carbon SeqNoExt.	−30.7	0.1	1.8	0.1	8.0	12.2	8.5

value for harvest revenues and for carbon storage but a much weaker correlation between the stand that provide the highest value for harvest revenues and for carbon sequestration measures (Fig. 2). This indicated a stronger conflict for carbon storage than for carbon sequestration with harvest revenues, which was also evident in the curves based on Pareto optimal plans in Fig. 5. Regarding the forest characteristics at the beginning of the time period, we found that mature, spruce-dominated forests were the best ones for providing both timber and carbon services. Age correlates well with tree biomass and carbon accumulation until a very advanced age in which net carbon uptake is thought to be balanced by respiration and increased mortality (Xu et al., 2012). Therefore, old trees store less efficiently carbon in live woody tissues, although they still can continue accumulating carbon (Luyssaert et al., 2008). Regarding tree species composition, Liski et al. (2001) found that a long rotation length was more favourable for the total carbon stock in Scots pine sites whereas a short rotation length seemed to be more favourable in Norway spruce sites. Therefore, the selection of tree species that most efficiently sequester/store carbon probably depends on the forest management regime applied.

We found a conflict between timber production and carbon services because, in most cases, the management regime that maximized timber was different from the one that maximized carbon. Moreover, for the small proportion of stands where a single regime maximized both services, most of the stands were classified as the *worst*. The stands designated as the *worst* were not very suitable for either services, but they may still be good stands from the climate policy perspective if they can provide carbon benefits at a low cost (see Juutinen et al., 2014 for cost-efficient study to improve forest biodiversity). Nevertheless, we also found situations in which both ecosystem services could be achieved with a single management regime (*matching* stands). In our landscape, these stands tended to be initially young with a relatively low proportion of spruce (Fig. S4). These results suggest three main strategies in resolving the conflict. First, one must identify and locate the win–win cases, i.e. stands where management regimes match and provide high levels of both ecosystem services (*best* stands). Second, for the rest of the stands one must find a combination of regimes that minimizes economic losses for a given level of carbon services, or vice versa. The third strategy is to spatially differentiate between the provision of timber and carbon related services. Our results suggest that 'land sharing' (provision of the two services from the same forest stand) and 'land sparing' (single service prioritization) are not exclusive strategies, although both are needed for solving the conflicts at the landscape scale.

Most of the studies analysing multiple ecosystem services focus on a single aspect of climate regulation: carbon storage (e.g., Maskell et al., 2013) or carbon sequestration (e.g., Nelson et al., 2009) but the consideration of both of them is interesting as different types of forests can be good at providing these different aspects of climate regulation. For instance, old-growth forests contain high amounts of carbon stored in the biomass and continue accumulating carbon in soils (Zhou et al., 2006). Forest management quite often targets at replacing old-growth forests with fast-growing young trees or tree species that can sequester carbon faster but, at the same time, the carbon storage is being reduced (Harmon et al., 1990). However, the capacity of boreal forests to store and sequester carbon are not the only elements contributing to climate regulation, as there are other processes involved, such as vegetation albedo (Betts and Ball, 1997; Betts, 2000; Bonan et al., 1992), ecosystem respiration (Valentini et al., 2000) or provision of aerosols that contribute to cloud formation (Spracklen et al., 2008). We urge for studies that incorporate as many of these processes as possible to get a more complete picture of the role that boreal forests play in climate regulation.

Our estimates of the predicted amount of carbon storage and sequestration were consistent with earlier studies in boreal forests (Mäkipää et al., 2011; Tamminen et al., 2012). Regarding carbon sequestration, in our study we took into consideration two measurements of it: one that includes carbon in harvested timber (carbon sequestered) and another that excludes the carbon in harvested timber (carbon sequestered non-extracted). The former considers wood products in the forest carbon and assumes that all carbon, once stored into timber, is permanently away from the atmosphere. The Kyoto Protocol (http://unfccc.int/resource/docs/convkp/kpeng.pdf) assumes a simple case that all the carbon is released to the atmosphere immediately after harvesting, thus, excluding the carbon storage in wood products. Both assumptions are unjustified because the end use of the wood products determines to what extent and for how long the carbon in wood products is retained from the atmosphere. Carbon in forest fuel is rapidly released back to the atmosphere but carbon in wooden building material and furniture is retained for a longer time (Cao et al., 2010). A realistic scenario is somewhere between these two extremes, and critically depends on the management decision and the markets for alternative wood products. Another important aspect affecting the carbon balance of forests are the substitution effects, i.e., there are different emission rates of carbon depending on the use of wood after harvesting (biofuel, sawn wood, pulp wood, etc.) (Pukkala, 2011). However, these factors are beyond the scope of our study, because the end use for the timber products once they leave the forest is out of landowner's decision (Asante and Armstrong, 2012).

Regarding the effect of different forest management regimes on the provision of carbon we found that no management regime alone was able to maximize carbon. Although setting aside stands was the most beneficial management for the provision of the three carbon measurements, a combination of regimes was more beneficial than a consistent application of the setting aside regime (Table 3). In agreement with Liski et al. (2001), we found that longer rotation lengths would be favourable for carbon, especially for carbon storage, whereas no-thinning strategies would be the most favourable ones for carbon sequestration. Refraining from thinning may also be economically profitable and beneficial for a broad range of boreal species (Mönkkönen et al., 2014; Tikkanen et al., 2012). Pukkala (2014) showed that thinning from above (a thinning that removes trees from the dominant classes) have positive effects on the carbon balance of forests. However, this is not in contradiction with our results because in this study we considered thinning from below (a thinning that removes the smaller trees).

Climate change is another factor that will affect the capacity of the forest to provide timber and preserve carbon. Most probably, in the Finnish boreal forest, carbon sequestration in living biomass will increase due to the increase in tree growth (Pukkala and Kellomäki, 2012), but the decomposition rate of dead organic matter may also increase (Shorohova et al., 2008; Tuomi et al., 2011). Adaptation strategies to increase timber extraction under climate change scenarios might include the reduction of the rotation length (Kellomäki et al., 2008). By contrast, our results showed that an optimal management, especially for carbon storage, should increase the rotation length, and no thinning (often increasing the rotation length) would be good for carbon sequestration. These two opposite needs for harvest revenues and carbon storage/sequestration may create a conflict in management priorities. Differentiating the provision of services from different types of stands ('land sparing') would solve the conflict. For the delivery of timber and carbon services we should focus on mature, spruce-dominated stands. Spruce-dominated stands are also the ones preserving a higher number of threatened species (Tikkanen et al., 2006) and this could create a conflict between timber extraction and biodiversity conservation. There are many uncertainties related to future climate projections (Knutti and Sedlacek, 2012) and many ways in which climate change can be measured (Garcia et al., 2014). Climate change was not considered in our analyses, but it will be interesting to include its effects on the provision of ecosystem services in future research to have more realistic predictions. Moreover, climate change can affect forests by altering the frequency, timing, duration and intensity of forest disturbances such as windstorms, insect outbreaks or fires (Dale et al., 2001).

5. Conclusions

We studied trade-offs between provisioning (revenues from timber selling) and regulating (carbon storage and sequestration) ecosystem services among alternative forest management regimes in a large boreal forest production landscape. Going beyond previous studies, we incorporated up to seven management regimes, ran simulations for a large landscape area with about 30,000 stands and identified management optima for a 50-year planning horizon. We were able to pinpoint "win–win" situations where it is possible to maximize both timber production and carbon storage/sequestration. We showed that the amount of carbon captured from the atmosphere and stored as biomass can be greatly increased with little monetary investment. In general, a good strategy to maintain both timber production and carbon storage/sequestration in production forests would be to diversify management regimes. The most favourable management regime for carbon storage/sequestration was "set-aside" followed by long rotation lengths and avoiding silvicultural thinning. These recommended management regimes are largely the same as those that have been promoted to maintain biodiversity in production forest landscapes (e.g., Mönkkönen et al., 2014, 2011). Therefore, current biodiversity conservation policy tools such as compensating forest owners for economic losses from environment-friendly forest management or setting aside forests with voluntary conservation agreements (Mönkkönen et al., 2009) also provide benefits in terms of climate regulation. Overall, our results show that forest owners and management planners can apply different strategies depending on the characteristics of forest stands: (a) identify "win–win" situations for the stands where it is possible to obtain both good levels of timber production and carbon storage/sequestration and (b) for the rest of the stands find a combination of management regimes that minimize economic losses for a target level of carbon storage/sequestration, or vice versa. This study emphasizes the importance of careful landscape-level forest management planning when targeting multiple ecosystem services.

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Appendix A. Detailed information on how different carbon compartments were calculated

Carbon biomass stored in living wood, dead wood and in extracted timber

The timber volume outputs from MOTTI were transformed into biomass using biomass expansion factors (BEFs) that are specific for tree species and stand age (Lehtonen et al., 2004). For the carbon stored in living wood, the tree components considered were: stem, stumps, foliage, branches, bark and transportation roots. For the carbon stored in dead wood, as the density of the wood was reduced through the decay process, the biomass was multiplied by the density for the five decay classes according to Mäkinen et al. (2006). The volume of the extracted timber in thinning and final harvest was the sum of the pulp and saw wood for each tree species. This volume was also converted into biomass using the BEFs but, in this case, only taking into account the stem compartment as the twigs, needles, etc. are left in the forest. In all cases, the final estimate of biomass (dry weight) was converted to carbon biomass by multiplying it by 0.5 (Intergovernmental Panel on Climate Change, 2003).

Residual carbon after thinning and final harvest

When there was a thinning or final harvest, the amount of cutting residues left on the forest floor (twigs, needles, stumps, etc.) were calculated as the difference in carbon stored in living wood ($\Delta W_{\text{Living C}}$) between two consecutive time steps (e.g., between years 10 and 5, years 15 and 10 and so on) and the amount of extracted carbon. We also took into account the growth rate of the trees during each five-year period between consecutive time steps. We used the following equation:

$$W_{i,\ \text{Residual C}} = (\Delta W_{i,\ \text{Living C}} + \text{Growth rate (5 yr)}) - W_{i,\ \text{Extracted C}}, \quad (1)$$

where i refers to each individual forest stand.

We also considered the decaying rate of the cutting residues not removed after thinning and final harvest:

$$W_{i,\ \text{Decayed Residual C}} = W_{i,\ \text{Residual C},\ i} \times \rho_i, \quad (2)$$

where ρ_i is the wood density values that depends on the year since death. The values were taken from Mäkinen et al. (2006).

Total carbon and three carbon measurements

For each time step, the total amount of carbon is the sum of the carbon biomass from each individual compartment:

$$W_{\text{Total C1}} = W_{\text{Living C}} + W_{\text{Dead C}} + W_{\text{Extracted C}} + W_{\text{Residual C}} + W_{\text{Decayed Residual C}}. \quad (3)$$

Carbon storage (CStor) was calculated as the average amount of carbon biomass in the study area during the 50-years period, across 11 time steps, following the equation for each stand:

$$W_{\text{CStor}} = \frac{\left(\sum_{i=1}^{11} W_{\text{Total C1}}\right)}{11}. \quad (4)$$

Carbon sequestered (Cseq) was calculated as the sum of changes in carbon stock across all time steps and for each stand (carbon biomass in harvested timber was included in the estimates):

$$W_{\text{Total C2}} = \Delta W_{\text{Living C}} + \Delta W_{\text{Dead C}} + \Delta W_{\text{Accum. Extracted C}} + \Delta W_{\text{Residual C}} + \Delta W_{\text{Decayed Residual C}}. \quad (5)$$

$$W_{\text{CSeq}} = \sum_{i=1}^{11} W_{\text{Total C2}}. \quad (6)$$

Carbon sequestered non-extracted (CseqNoExt) was calculated as the sum of changes in carbon stock across all time steps and for each stand (carbon biomass in harvested timber was not included in the estimates):

$$W_{\text{Total C3}} = \Delta W_{\text{Living C}} + \Delta W_{\text{Dead C}} + \Delta W_{\text{Residual C}} + \Delta W_{\text{Decayed Residual C}}. \quad (7)$$

$$W_{\text{CSeqNoExt}} = \sum_{i=1}^{11} W_{\text{Total C3}}. \quad (8)$$

Appendix B. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.ecoser.2015.02.003.

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