Pukkala *Forest Ecosystems* (2018) 5:11
DOI 10.1186/s40663-018-0131-5

Forest Ecosystems

RESEARCH Open Access

Carbon forestry is surprising

Timo Pukkala

Abstract

Background: Forestry offers possibilities to sequestrate carbon in living biomass, deadwood and forest soil, as well as in products prepared of wood. In addition, the use of wood may reduce carbon emissions from fossil fuels. However, harvesting decreases the carbon stocks of forests and increases emissions from decomposing harvest residues.

Methods: This study used simulation and optimization to maximize carbon sequestration in a boreal forest estate consisting of nearly 600 stands. A reference management plan maximized net present value and the other plans maximized the total carbon balance of a 100-, 200- or 300-year planning horizon, taking into account the carbon balances of living forest biomass, dead organic matter, and wood-based products

Results: Maximizing carbon balance led to low cutting level with all three planning horizons. Depending on the time span, the carbon balance of these schedules was 2 to 3.5 times higher than in the plan that maximized net present value. It was not optimal to commence cuttings when the carbon pool of living biomass and dead organic matter stopped increasing after 150–200 years.

Conclusions: Letting many mature trees to die was a better strategy than harvesting them when the aim was to maximize the long-term carbon balance of boreal Fennoscandian forest. The reason for this conclusion was that large dead trees are better carbon stores than harvested trees. To alter this outcome, a higher proportion of harvested trees should be used for products in which carbon is stored for long time.

Keywords: Carbon balance, Carbon sequestration, Decomposition model, Wood product model, Boreal forest

Background

Forest management for climatic benefits, so-called carbon forestry, is currently a hot topic (Bellassen and Luyssaert 2014). Opinions about the overall role of forests in carbon sequestration and climate change mitigation vary widely as do opinions about climatically good forest management. The results of some studies indicate that a good way to mitigate climate change through forest management is to let the forests grow and accumulate carbon in living biomass and dead organic matter (Pukkala 2014; Heinonen et al. 2017). Other studies suggest that forests should be used to maximize their climatic benefit, because the use of wood products may reduce carbon emissions from fossil fuels (Liu and Han 2009). Wood and other forest biomasses can be burned for energy, and sawn wood can be used for construction to reduce carbon releases from cement and steel industry. Cellulose and pulp can be manufactured into products that replace oil-based plastic products.

In the short term, reducing harvests and increasing forest biomass is the best strategy in carbon sequestration (Heinonen et al. 2017; Pukkala 2017). However, since the growth rate of trees decreases when the trees get old and stands become too dense, it may become better to harvest trees to make space for biomass growth. Harvested wood can be used in products that decrease emissions from fossil fuels. Pukkala (2017) calculated that, in managed boreal forest, the no-harvesting option had a better annual carbon balance than normal sustainable forest management for about 140 years, after which the ranking was reversed. However, the total carbon balance of the analyzed 200-year period was better for the no-cutting scenario. Heinonen et al. (2017) found that the 90-year carbon balance of Finnish forests was the better, the lower was the cutting level. Knauf et al. (2015) found that a wood use strategy was equally good as a conservation strategy already during a 40-year time span.

Correspondence: timo.pukkala@uef.fi
University of Eastern Finland, PO Box 111, 80101 Joensuu, Finland

The reason for the good performance of the no-cutting option for so long time may be related to the longevity and slow growth rate of boreal trees and forests. In addition, large dead trees decompose slowly (Tuomi et al. 2011), which means that the carbon stock of dead organic matter continues to increase after the net increment of living biomass ceases. Therefore, old forests may be carbon sinks although their growing stock volume no longer increases (Zhou et al. 2006; Luyssaert et al. 2008).

Knowing that refraining from cutting is good in the short term but cutting becomes better in a longer term (e.g. Pukkala 2017) does not answer the question of how forests should be managed to maximize their carbon sequestration. One possibility is to decrease cuttings and increase carbon stock at first, and when the growth rate of biomass slows down, increase cuttings to the level of biomass growth. This strategy may seem even evident in Finnish forests, taking into account that increasing stand volume and biomass would also increase volume growth and carbon sink (Heinonen et al. 2017). This kind of cutting schedule has the benefit that the carbon balance of the first decades is good, due to rapidly increasing carbon stock of forest biomass. However, it is not known for how long cuttings should be restricted, or how much should be cut during the transitional period.

The above discussion shows that the use of forest for maximal climatic benefit is a complicated issue. In long-term analyses, relevant elements are for instance the longevity of trees and wood-based products, and the decomposition rate of deadwood. Conclusions about the effect of cuttings on carbon sequestration depend on the length of the analyzed time span (Knauf et al. 2015; Pukkala 2017). Forest protection may not be the best long-term strategy for climate change mitigation but when climatic benefits are required in near future, sustainable harvesting may be clearly worse than protection. In addition, the carbon balance of forest utilization depends on the carbon releases of management, harvesting, transport and manufacturing, and avoided emissions due to the use of wood.

Due to the prevailing uncertainty about forest management for maximal climatic benefit, Bellassen and Luyssaert (2014) propose that forest management should use win–win strategies, which increase both forest stocks and timber harvest, through protecting trees from animals, or replacing dying or low productivity forests by healthier and more vigorous stands. They remind that decomposing harvest residues and roots increase the carbon emissions of cuttings, and these emissions are only slowly compensated for by increased use of wood products. This would lengthen the period during which avoiding harvests is a competitive strategy in climate change mitigation.

Previous studies on the carbon balance of Finnish boreal forests have either compared a few management scenarios (Zubizarreta-Gerendiain et al. 2016; Heinonen et al. 2017; Pukkala 2017) or maximized carbon sequestration at the stand level (Pohjola and Valsta 2007; Pukkala 2011; Pukkala et al. 2011). Several studies have shown that increasing importance of carbon sequestration leads to longer rotations, higher stand densities and harvesting saw logs instead of pulpwood (Liski et al. 2001; Pohjola and Valsta 2007; Pingoud et al. 2010; Pukkala 2011; Pukkala et al. 2011; Niinimäki et al. 2013; Pihlainen et al. 2014). The management of large forest areas has rarely been optimized for maximal long-term carbon sequestration in biomass, deadwood and products. Pukkala (2014) conducted forest level optimizations for a 30-year period. Carbon balance was maximized with very low cutting level, which is an obvious result for such a short time period.

The aim of this study was to optimize forest management for maximal long-term carbon balance, taking into account all relevant carbon pools: living biomass, dead organic matter (forest soil), and wood based products. In addition, releases from harvesting, transport and manufacturing and avoided emissions from fossil fuels were taken into account. Calculations were made for 100-, 200- and 300-year time horizons, to find out how the time span of the analysis affects the conclusions. Based on the projected stand management schedules and their carbon balances, trade-off curves were calculated between harvested volume and carbon sequestration.

Methods

Calculations were made for a forest estate of 502 ha located in southern Finland (Table 1). The forest consisted of 593 stand compartments. The average growing stock volume was 127 $m^3 \cdot ha^{-1}$ (usable volume 116 $m^3 \cdot ha^{-1}$), of which Scots pine (*Pinus sylvestris* L.) accounted for 33%, Norway spruce (*Picea abies* (L.) H. Karst.) 30%, silver birch (*Betula pendula* Roth) 22%, downy birch (*B. pubescens* Ehrh.) 5%, aspen (*Populus tremula* L.) 6% and other species 4%. More than half (52%) of the stands represented mesic sites (*Myrtillus* type), 27% were herb-rich (*Oxalis-Myrtillus* type) and the remaining 11% were sub-xeric (*Vaccinium* type).

Treatment alternatives were simulated for each stand for ten time periods so that the timing and type of cuttings varied. A part of the schedules represented continuous cover management, which means that final felling was never simulated. In even-aged management, the final felling was clear-cutting, followed by site preparation and planting on mesic and herb-rich sites, and site preparation and sowing pine seeds on sub-xeric sites. If the stand consisted of two distinct canopy layers, one of the treatment schedules included the removal of

Table 1 Area and average growing stock volume (usable volume) in different stages of stand development

Stage of stand development	Area	Mean volume ($m^3 \cdot ha^{-1}$)			
	(ha)	Saw log	Small log	Pulpwood	Total
Open area	1.7	0	0	0	0
Seedling & sapling stand	78.2	0	0	1	1
Seed & shelter tree stand	26.7	66	1	43	110
Pulpwood-sized forest	67.5	13	2	48	63
Saw-log sized thinning forest	168.0	60	7	79	146
Financially mature forest	109.3	123	4	65	192
Young uneven-aged forest	51.1	42	5	39	86
Total	502.5	58	4	54	116

the upper canopy. Every stand had also a schedule in which there were no cuttings.

The length of each of the ten time periods was 10, 20 or 30 years, resulting in 100-, 200- and 300-year total simulation horizon. The average number of different treatment schedules per stand was 67 when the length of the sub-period was 10 years whereas 20- and 30-year sub-periods resulted in 95 and 100 schedules per stand, respectively.

Stand development was simulated by using the individual-tree models of Pukkala et al. (2009, 2013) for diameter increment, survival and tree height. The gradual appearance of advance regeneration (ingrowth) was also simulated using the models of Pukkala et al. (2013). The biomasses of different parts of trees were calculated with biomass models (Repola 2008, 2009). Each harvested tree was partitioned into timber assortments (Table 2) using the taper models of Laasasenaho (1982). Quality deductions in saw log volume were made according to the model of Mehtätalo (2002) and the results on Malinen et al. (2007).

The carbon balance and carbon stock were calculated for each schedule and for the following three carbon stores: living biomass, dead organic matter, and wood-based products. All three carbon pools were initialized. The living biomass pool of a stand was initialized with biomass models and the carbon contents of different biomass components. The carbon pools of products and dead organic matter were initialized with models (Pukkala 2014).

Inputs to the dead organic matter pool consisted of annual litter fall (both above- and below-ground litter), mortality, and harvest residuals. The Yasso07 model (Liski et al. 2009; Tuomi et al. 2011) was used to simulate the decomposition of dead organic matter.

The carbon pool of wood-based products consisted of sub-pools for the following end product categories: biofuel, construction wood, mechanical mass products, and chemical mass products. Harvested trees were first divided into saw log, pulpwood and biofuel assortments, and saw log and pulpwood were further subdivided into end product categories (Liski et al. 2001; Pukkala 2014). For example, when a sawlog was processed in sawmill, less than 50% of its volume become sawn wood, and the rest (sawdust, surfaces of logs) was used in mass industry or as biofuel. In chemical mass industry, around 50% of the biomass of pulpwood logs was converted into cellulose and paper products and the rest was used as biofuel.

Each category was associated with the following parameters affecting the carbon balance of the sub-pool (Table 3): manufacturing release, avoided emissions due to the use of wood-based product, annual disposal rate, and end-of-life reuse rate (Liski et al. 2001; Zubizarreta-Gerendiain et al. 2016; Heinonen et al. 2017). At the end of life (for instance when a wooden building was demolished), a part of disposed wood was assumed to be used as biofuel, leading to reduced emissions from fossil fuels. Carbon releases from timber harvesting and transport were also taken into account when calculating the carbon balance of wood-based products.

More detailed descriptions of the carbon balance calculation can be found from previous studies (e.g., Pukkala 2014, 2017). The values of the parameters that determine the carbon balance of wood-based products are shown in

Table 2 Assortments and their roadside prices used in the calculations

Assortment	Minimum top diameter (cm)	Minimum log length (m)	Roadside price (€·m^{-3})
Pine saw log	15	4.3	57
Pine small log	13	3.4	32
Pine pulpwood log	8	2.0	30
Spruce saw log	16	4.3	57
Spruce small log	13	3.4	32
Spruce pulpwood log	9	2.0	30
Birch saw/veneer log	17	3.4	45
Birch pulpwood log	8	2.0	30
Aspen saw log	17	4.3	40
Aspen pulpwood log	8	2.0	20
Alder pulpwood log	8	2.0	10

Table 3 Disposal rates, manufacturing releases, avoided emissions from fossil fuels, and reuse rates for different product categories

Product category	Manufacturing release ($tC{\cdot}tC^{-1}$)	Annual disposal rate	Avoided emissions ($tC{\cdot}tC^{-1}$)	Reuse rate
Sawn wood, plywood	0.032	0.02	1.0	0.65
Mechanical mass	0.48	0.10	0.15	0.8
Chemical mass	0.13	0.10	0.15	0.8
Biofuel	0.05	0.30	0.65	0

Disposal rate is the proportion of products discarded annually. Reuse rate is the proportion of discarded products used as biofuel

Table 3. The incomes from timber sales were calculated as the difference between the roadside value of harvested trees (Table 2) and harvesting costs. The models of Rummukainen et al. (1995) were used to calculate harvesting costs.

Optimization was used to select the best combination of treatment schedules for the 593 stands of the case study area. Alternative management plans (scenarios) were obtained by using different objective variables:

- Maximize net present value with a 3% discount rate
- Maximize the total carbon balance of the whole simulation period
- Maximize discounted carbon balance, to have more weight on the first time periods

The used approach represents the standard method of modern forest management planning (Borges et al. 2002; Kangas et al. 2008), which consists of simulating treatment alternatives for the stands and using combinatorial optimization for finding the ideal combination of these schedules. However, because there were no constraints and the values of objective variables in different stands were independent of each other, optimization for the three basic scenarios listed above was equal to picking the best schedule for each stand.

Additional optimization ("Mixed strategy") was conducted to test the hypothesis that good carbon forestry would consist of letting the biomass increase at first, after which cuttings are increased to the level of annual increment. In this optimization problem, constraints were used for harvested and growing stock volume to have the wanted initial increase in growing stock volume. The growing stock volume was gradually increased from 127 to 300 $m^3{\cdot}ha^{-1}$ during 90 years after which it remained constant. The annual harvest of this period was 2.5–3 $m^3{\cdot}ha^{-1}{\cdot}a^{-1}$, after which it was about 3.5 $m^3{\cdot}ha^{-1}{\cdot}a^{-1}$.

Another scenario was produced for the 100-year time span, in which NPV with a 3% discount rate was maximized but the substitution rate of sawn wood (avoided emissions from fossil fuels) was increased from 1 to 2 $tC{\cdot}tC^{-1}$ (Sathre and O'Connor 2010). It was also assumed that 2/3 of the cutting residues (branches and tree tops) of final felling sites were harvested as biofuel and sold with €2 per one ton of dry mass (Zubizarreta-Gerendiain et al. 2016). In this scenario, the manufacturing releases and substitution effects of mechanical and chemical pulp were zero. This last assumption was based on the assumption of leakage, which means that reduced production of pulp and paper products in one region leads to increased production somewhere else. Therefore, on the global scale, both releases and substitution effects remain the same. This scenario is referred to as the HSR scenario (HSR refers to "high substitution rate").

Results

Optimal management for maximal carbon balance

When the planning horizon consisted on ten 10-year periods, maximization of NPV resulted in a cutting level of approximately 5.5 $m^3{\cdot}ha^{-1}{\cdot}a^{-1}$, the 10-year harvest intensity ranging from 3.5 to 7 $m^3{\cdot}ha^{-1}{\cdot}a^{-1}$ (Fig. 1, top). When the total carbon balance of the 100-year period was maximized, there were some cuttings during three first periods, after which the harvested volume was very small. Maximization of discounted carbon balance, which is equal to giving more importance to the first 10-year periods, decreased the cuttings of the first periods. This decrease was not compensated for by increased cuttings during later periods.

The mean annual carbon balance of the Max NPV scenario was positive and of the magnitude of one $tC{\cdot}ha^{-1}{\cdot}a^{-1}$, implying that forestry was carbon sink (Fig. 1, bottom). When carbon balance was maximized, the sink was much stronger (3.5 $tC{\cdot}ha^{-1}{\cdot}a^{-1}$ on average during the 100-year period) with an ascending-descending temporal pattern. Maximizing discounted carbon balance led to improved balance for the first periods and lower balances for later periods, as compared to the Max C scenario.

Differences in the amount and timing of cuttings led to obvious differences in carbon stocks (Fig. 2). In the Max NPV scenario, all three carbon pools (living biomass, dead organic matter, wood-based products) remained rather constant because the cutting level was close to volume growth. In the other scenarios, the carbon pools on living biomass and dead organic matter increased for the whole 100-year period. The carbon pool of products decreased, because of the gradual disposal of old products and small quantity of new products due to low cutting level. At first, the living biomass pool increased fastest, but the

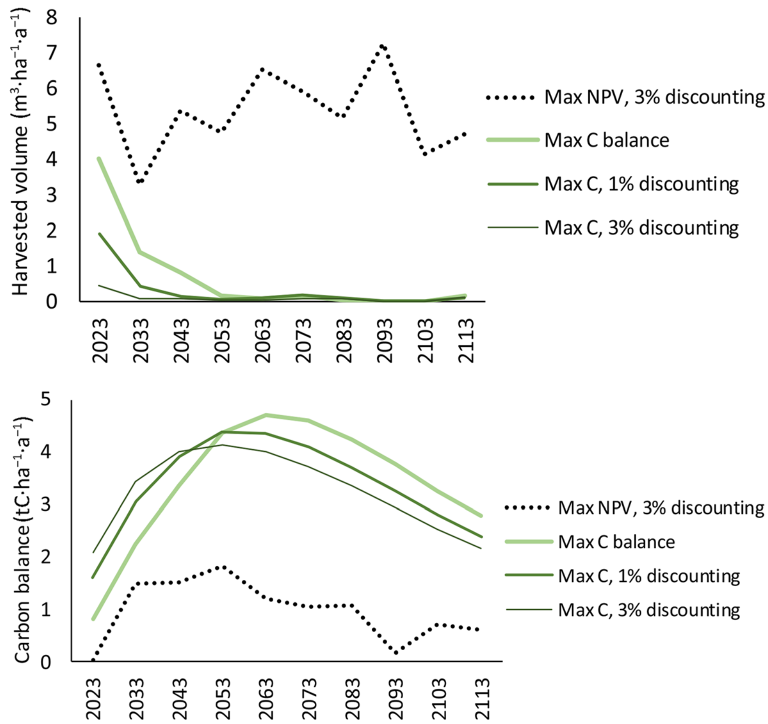

Fig. 1 Harvested volume and carbon balance of ten 10-year periods when net present value (Max NPV), carbon balance (Max C) or discounted carbon balance (Max C, 1%/3% discounting) is maximized

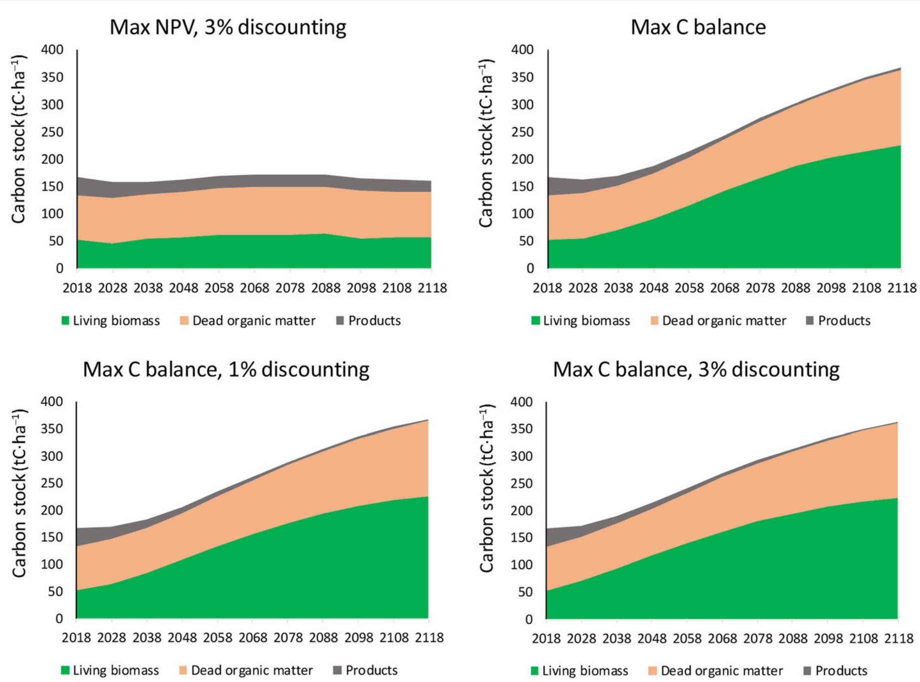

Fig. 2 Development of carbon stocks during a 100-year period when net present value (Max NPV), carbon balance (Max C balance) or discounted carbon balance (Max C balance, 1%/3% discounting) is maximized

increase of the carbon pool of dead organic matter continued longer.

Effect of time span

It may be argued that the low-cutting management of the Max C scenarios (with or without discounting the 10-year carbon balances) cannot be optimal in the longer run. This is because the carbon pools of living biomass and dead organic matter eventually stop increasing with a consequence that their carbon balances approach to zero. In the case study forest of this study, the carbon pool of living biomass stopped increasing after about 150 years, after which the size of the dead organic matter pool continued to increase for another 60–70 years (Fig. 3). To analyze the effect of the length of the simulation horizon, all analyses were repeated using ten 20- or 30-year periods in simulation, leading to a total horizon of 200 or 300 years.

When NPV was maximized with 100-, 200- or 300-year simulation period, the cutting level of the first 100-period remained the same, but there was less temporal variation when the length of the sub-period increased (Fig. 4, top). When the total carbon balance of the whole simulation period was maximized, the length of the simulation period had a clear effect on the results (Fig. 4, middle): the longer was the time span, the longer cuttings were continued. In all cases, almost all cuttings were prescribed for the first time periods. The results imply that extending the length of the time span for which carbon balance is maximized, leads to increased cuttings (and decreased carbon balance) of the first decades. The cutting level of these first decades was about 3 $m^3 \cdot ha^{-1} \cdot a^{-1}$, which is 2.5 $m^3 \cdot ha^{-1} \cdot a^{-1}$ less than in the Max NPV scenario.

Compared to the Max C scenario, maximization of discounted carbon balance led to decreased cutting levels during the first decades (Fig. 4, bottom). This is logical because the carbon balance of the first decades had more importance, and the best way to improve the carbon balance of near future was to decrease cuttings.

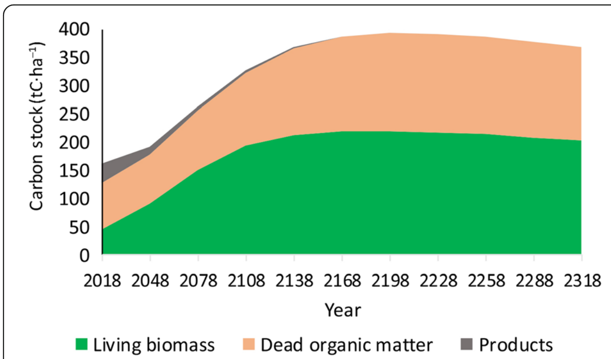

Fig. 3 Development of carbon stocks during a 300-year period when carbon balance is maximized with 1% discount rate

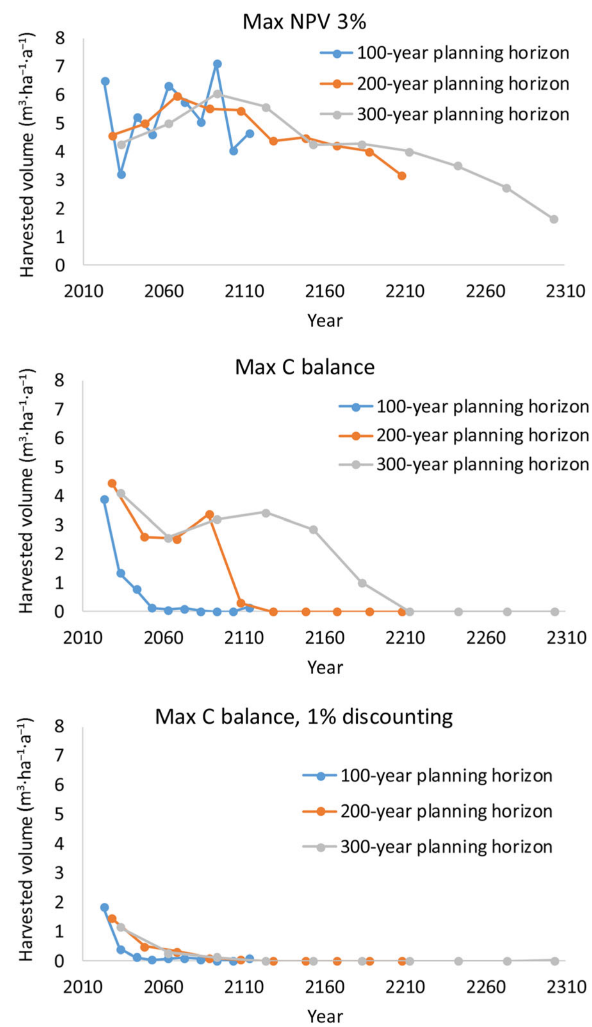

Fig. 4 Effect of the length of planning horizon on harvested volume when net present value (top), carbon balance (middle) or discounted carbon balance (bottom) is maximized

However, a less obvious result was that decreased cuttings during the first decades were not compensated for by increased cuttings during later periods.

When NPV was maximized with 100-, 200- or 300-year simulation period, the annual carbon balance was always at the level of 0.5–1 $tC \cdot ha^{-1} \cdot a^{-1}$ (Fig. 5, top). Temporal variation in periodical carbon balance decreased with increasing length of the sub-period. When the objective was to maximize carbon balance, with the same importance on near and distant future, increasing length of planning horizon led to delayed, lower and longer-lasting peak years (Fig. 5, middle). Conducting some cuttings during the first decades made it possible to lengthen the period of good carbon balance. When the length of the simulation period was 300 years, the overall level of annual carbon balance was 1.5–2 $tC \cdot ha^{-1} \cdot a^{-1}$, which is about three times more than in the Max NPV scenario.

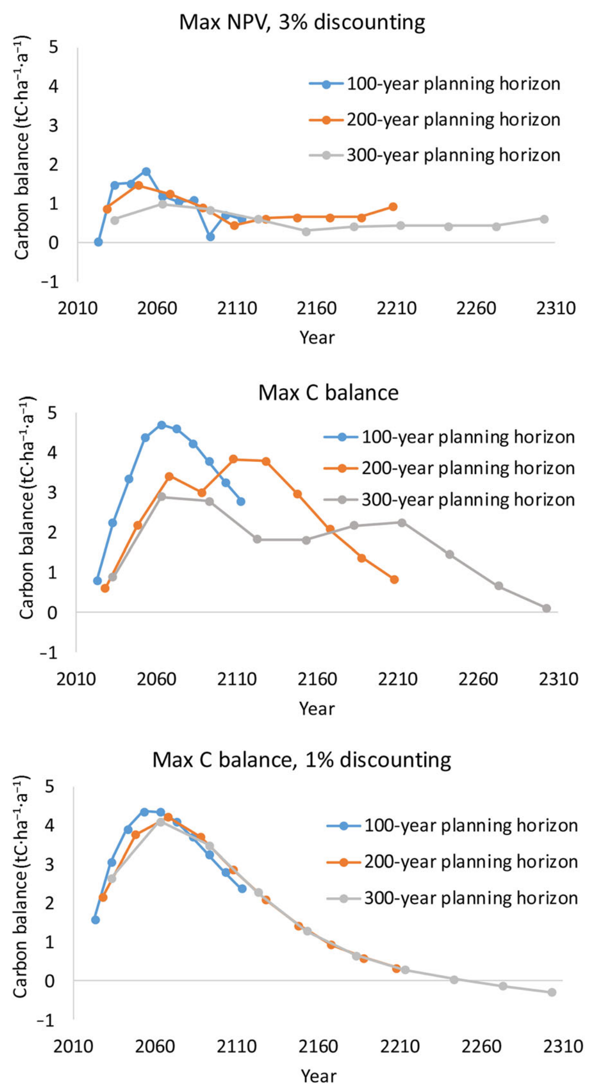

Fig. 5 Effect of the length of planning horizon on carbon balance when net present value (top), carbon balance (middle) or discounted carbon balance (bottom) is maximized

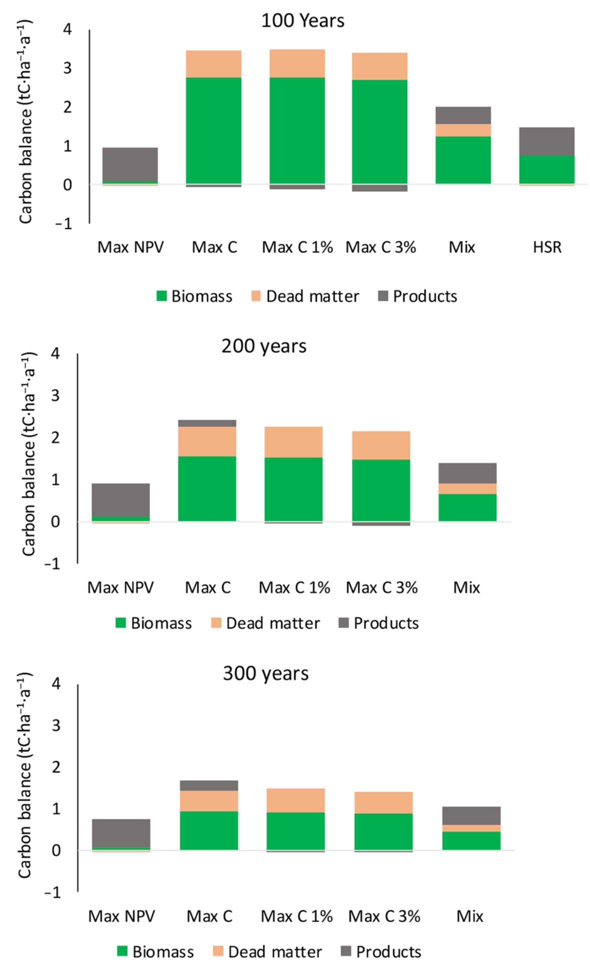

Fig. 6 Mean annual carbon balance of 100-, 200- or 300-year planning horizon when net present value (Max NPV), carbon balance (Max C) or discounted carbon balance (Max C 1%, Max C 3%) is maximized. "Mix" refers to a scenario where growing stock volume increases for 90 years, after which harvest is equal to volume growth. HSR maximizes NPV with a 3% rate but the substitution rate of saw log is assumed to be higher, pulp products are carbon neutral and cutting residues are harvested for fuel feedstock

Maximizing discounted carbon balance led to similar temporal distribution of the carbon balance during the first 100 years, irrespective of the length of the analyzed period (Fig. 5, bottom). This objective function led to very low cutting level with all three time spans (Fig. 4, bottom). Therefore, the results mean that when the carbon balance is maximized with more importance on near future, conclusions about optimal management are not sensitive to the length of the time span of the analysis, if the time span is at least 100 years.

Synthesis of results

A summary of the mean annual carbon balance is shown in Fig. 6, which shows the effect of objective variable and length of the calculation horizon on the carbon balances of biomass, dead organic matter, and wood-based products. A longer time span of the analysis led to decreased mean annual carbon balances of those scenarios in which carbon balance was maximized. The gap between the Max NPV and Max C scenarios got narrower as the length of the calculation period increased. However, even with a 300-year time span, scenarios that maximized carbon balance had two times higher mean annual carbon balance than in the Max NPV scenario.

The mixed strategy, which was hypothesized to be good for carbon sequestration, was better than Max NPV but worse than strategies in which carbon balance was maximized. In the mixed strategy, the carbon balance of living biomass was about 1.5 $tC{\cdot}ha^{-1}{\cdot}a^{-1}$ for 90 years while the carbon balance of products was at the level of 0.4 tC·ha^{-1}·a^{-1}. After 90 years, when harvests were increased to the same level as volume increment, the carbon balance of living biomass was near zero while the carbon balance of products increased to 0.6 tC·ha^{-1}·a^{-1}.

The HSR scenario resulted in better balance than obtained with original parameter values (Max NPV) but the carbon balance of HSR was still far from the carbon balances of scenarios where carbon balance was maximized.

Simulations for 100, 200 and 300 years (with the baseline values of substitution rates and other parameters) made it possible to analyze the trade-offs between harvested volume and carbon balance (Fig. 7). With all time spans, increasing harvesting intensity decreased carbon balance. Maximal carbon balance was obtained at a cutting level of about 1.5 m^3·ha^{-1}·a^{-1}. Refraining from all cuttings did not maximize carbon balance. However, maximizing carbon balance with more weight on near future would lead to very low cutting level (see Fig. 4, bottom).

Increasing length of the time span of simulation decreased both the mean annual carbon balance and the mean annual harvest. The reason for decreasing carbon balance was that the accumulation rate of carbon in living biomass and dead organic matter slowed-down with longer time spans. The decrease in the maximum harvest intensity is also logical because the effect of the initial growing stock on mean annual harvest decreased when the length of the time horizon increased.

Discussion

Optimal forest management for maximal carbon sequestration turned out to be surprising in the sense that whenever there were cuttings, they were prescribed in the beginning of the analyzed time horizon. When the length of the analyzed time horizon increased, the period

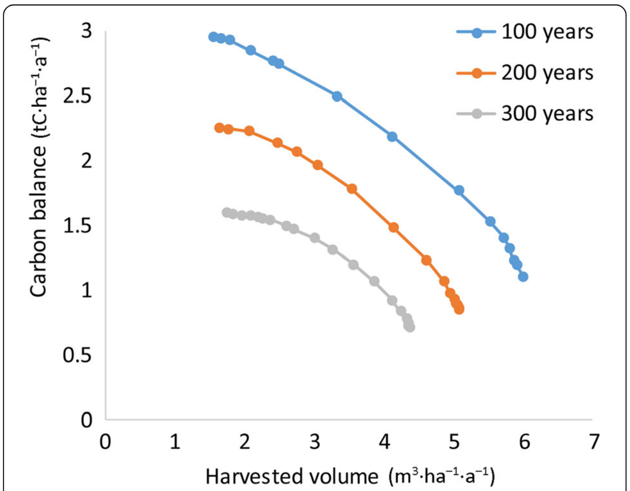

Fig. 7 Trade-off curves between mean annual carbon balance and mean annual harvest when the length of the simulation period is 100, 200 or 300 years

during which cuttings were conducted also increased. The results were against the assumption that it might be optimal to increase the growing stock volume at first, and when substantial increases are no longer possible, it would be optimal to increase harvests. The results in fact showed that a completely opposite strategy was the best for carbon sequestration.

Logically, when more weight was given to the carbon balance of near future, it was optimal to decrease cuttings during the first 10-year periods. However, the outcome that cuttings prescriptions were removed completely instead of postponing them to later periods was an unexpected result.

It may be asked why it was not optimal to commence cuttings when biomass stopped increasing and when the size of the carbon pool of dead organic matter stabilized. There are two possible explanations, which affect simultaneously. The first is that when the stands are left to grow without cutting, their trees become larger, and large dead trees are better carbon stores than smaller dead trees (Fig. 8, left). When a pine tree dies at 10 cm dbh, the decomposition rate of its stem is two times faster than in a pine whose dbh is 50 cm at the moment of death.

Another reason is that, in a boreal forest, a large dead conifer often has a better carbon balance than a large cut conifer. Therefore, for the carbon balance of forestry, it is better to let large trees die instead of harvesting them. This is visualized in Fig. 9, which shows that carbon is released to atmosphere clearly faster from a harvested tree, as compared to a dead tree. The diagram is based on the same decomposition model (Yasso07, Liski et al. 2009) and product model (Pukkala 2014) as used in the other analyses of this study. After 100 years, the remaining carbon stock of a dead tree is over three times larger than the carbon stock of a cut tree.

If a dead tree has a better carbon balance than a harvested tree, it might be asked why there were cuttings in the beginning of the analyzed time period when carbon balance was maximized without time preferences. Looking at the selected treatment schedules of individual stands revealed that some stands were converted into structures, which made it possible to maintain good carbon balance for a long time. These post-cutting structures were conifer-dominated stands, which can sequestrate carbon for long time, and reach a high growing stock volume and large average tree size, resulting in high carbon stock of both living biomass and dead organic matter. For example, mature birch and pine trees were removed from stands having fully stocked spruce regeneration. Sparse stands of mature trees were also cut and replaced by fully stocked conifer-dominated stands.

The results agree with earlier studies, which show that the annual carbon balance of a sustainable cutting schedule eventually becomes better than a no-cutting or low-cutting

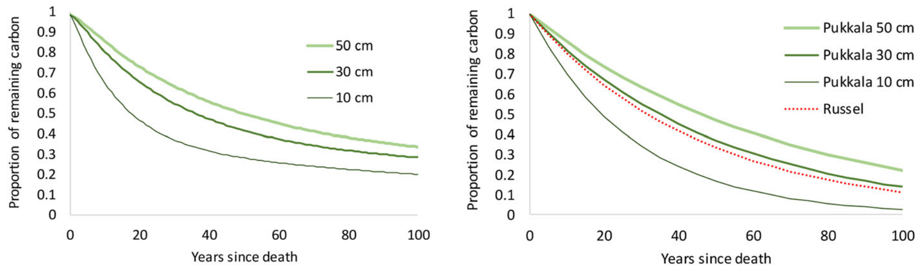

Fig. 8 Decomposition of pine stem as a function of time and dbh of the tree according to Yasso07 model (left), and according to two other studies (Pukkala 2006; Russell et al. 2015)

schedule (e.g. Pukkala 2017). In this study, the ranking changed in favor of sustainable cutting after 160–200 years (Fig. 5). However, the total carbon balance of all years was better for the low-cutting strategies for at least 300 years. This is in line with Morison et al. (2012) who concluded that avoided emissions from fossil fuels is the only climatic benefit of harvesting, which does not exhibit saturation in a long run. However, the size of this contribution may not match the in-forest sequestration of a low-cutting scenario for many rotations or decades (see also Fortin et al. 2012).

The conclusion of this study, and especially the comparison of harvested and dead tree as a carbon store, depend on the models used calculations. The Yasso07 decomposition model has been used widely and it has been validated in several studies (e.g., Liski et al. 2005; Rantakari et al. 2012; Didion et al. 2014). The model is based on large datasets collected in several countries (Tuomi et al. 2009). The product model used in this study has been compared to other models by Brunet-Navarro et al. (2016), who evaluated that the model structure is close to reality and reflects all relevant processes. However, product life spans and the associated releases and avoided emissions may change when new construction materials are developed. Therefore, parameters related to wood products should be regarded as assumptions rather than factors that have a single correct value.

The used decomposition model was compared to two other models based on the simple decay curve $Y_t = Y_0 \times \exp(-kt)$ where t is time since death and k is annual decay rate (Fig. 8). The Yasso07 model predicts slower decomposition than the two other models shown in the right-hand-side diagram of Fig. 8, where the annual decomposition rate (k) is based on either Pukkala (Fig. 3 in Pukkala 2006) or the model of Russell et al. (2015, their equation for the 50% percentile of annual decomposition rate). Russell et al. (2014) calculated the annual decomposition rate for downed wood debris of several tree species in eastern USA. They ranged from 0.024 to 0.040 for conifers, and the decay rate increased with increasing temperature of the region. A rate of 0.024 would mean that 10% of the biomass of downed wood is not decayed after 100 years, which is close to the dotted curve in the right-hand-side diagram of Fig. 8. However, the results of Russell et al. (2014) correspond to climates warmer than Finland and tree sizes smaller than trees that die in mature stands of the southern part of boreal forest. According to Laiho and Prescott (2004) a decay rate of 0.024–0.027 is typical of Norway spruce and Scots pine stems in northwestern Russia.

Climate change has an effect on the decomposition rate of dead organic matter, which may impact the comparison of the carbon balance of dead vs. cut tree. According to the Yasso07 decomposition model, a 2 °C

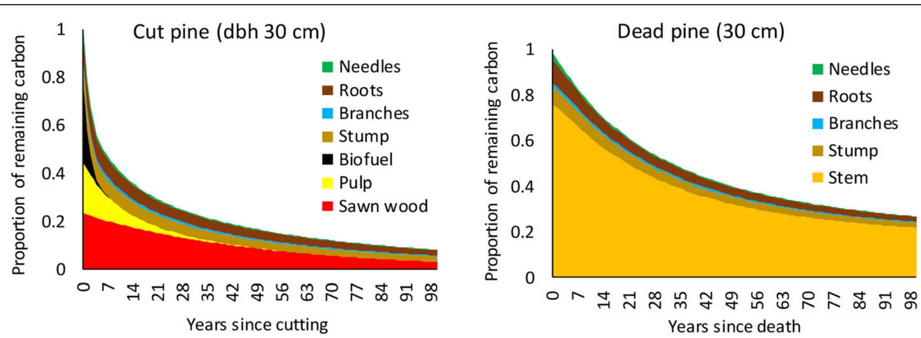

Fig. 9 Proportion of remaining carbon in a cut pine (left) and a dead pine (right) when the dbh of the tree is 30 cm. The diagrams are based on the same assortment volumes, biomasses and decomposition rates as used in the other calculations of this study

increase in mean annual temperature would increase the decomposition rate of a 30-cm-thick conifer stem by 5%–10%. Since the increase in temperature is gradual, the effect of climate change of the conclusions of this study would be small.

Most probably there is much variation in the decomposition rate of large trees, depending for instance on whether the dead trees are snags of downed stems. Snags usually decompose slower than downed wood (Laiho and Prescott 2004). It might be assumed that when large trees die in dense conifer stands due to senescence, they may remain standing for a long time, which slows-down their decomposition rate. Large pine snags with high resin content may endure for centuries, acting as very durable carbon stores.

Conclusions

The results of this study suggest that, when the long-term carbon balance of forestry is maximized, harvesting level should be low. This leads to mortality and accumulation of carbon in dead trees. It was concluded that the main reason for this result is that, in boreal forests, large dead trees are often better carbon stores than harvested trees. The carbon balance of a dead tree may be better than that of a harvested tree, even when the avoided emissions from fossil fuels are included in the carbon balance of harvested trees.

One reason for the low carbon balance of harvested trees is the small proportion of sawn wood. When a large tree is harvested, only about 20% of the total biomass of the tree is converted into sawn wood, which can be used to store carbon in buildings and other structures. The carbon balance of pulp and paper products is not high, since only a part of paper products replace fossil-based products, and pulp and paper industry consumes much energy. A way to improve the carbon balance of harvested trees is to increase the share of construction wood. This can be achieved for instance by developing and using new product types, such as engineered wood products, which can be manufactured from small-sized and lower-quality timber.

Acknowledgements
Not applicable.

Funding
Not applicable.

Availability of data and materials
Not applicable.

Authors' contributions
TP conducted the analyses and wrote the manuscript.

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The author declares that he has no competing interests.

Received: 27 November 2017 Accepted: 15 January 2018
Published online: 09 March 2018

References

Bellassen V, Luyssaert S (2014) Managing forests in uncertain times. Nature 506:153–155
Borges JG, Hoganson HM, Falcão AO (2002) Heuristics in multi-objective forest management. In: Pukkala T (ed) Managing Forest ecosystems 6. Kluwer Academic Publisher, Dordrecht, pp 119–151
Brunet-Navarro P, Jochheim H, Muys B (2016) Modelling carbon stocks and fluxes in the wood product sector: a comparative review. Glob Chang Biol. https://doi.org/10.1111/gcb.13235
Didion M, Frey B, Rogiers N, Thürig E (2014) Validating tree litter decomposition in the Yasso07 carbon model. Ecol Model 291:58–68
Fortin M, Ningre F, Robert N, Mothe F (2012) Quantifying the impact of forest management on the carbon balance of the forest-wood product chain: a case study applied to even-aged oak stands in France. Forest Ecol Manag 279:176–188
Heinonen T, Pukkala T, Mehtätalo L, Asikainen A, Kangas J, Peltola H (2017) Scenario analyses for the effects of harvesting intensity on development of forest resources, timber supply, carbon balance and biodiversity of Finnish forestry. Forest Policy Econ 80:80–98
Kangas A, Kangas J, Kurttila M (2008) Decision support for forest management. In: Gadow KV, Pukkala T, Tomé M (eds) managing Forest ecosystems. Dordrecht: Springer Science + Business Media, pp 222. ISBN 978-1-4020-6786-0
Knauf M, Köhl M, Mues V, Olschofsky K, Frühwald A (2015) Modeling the CO_2-effects of forest management and wood usage on a regional basis. Carbon Balance Manage 10: 13. https://doi.org/10.1186/s13021-015-0024-7
Laasasenaho J (1982) Taper curve and volume equations for pine spruce and birch. Communicationes Instituti Forestalis Fenniae 108:1–74
Laiho R, Prescott CE (2004) Decay and nutrient dynamics of coarse woody debris in northern coniferous forests: a synthesis. Can J For Res 34:763–777
Liski J, Palosuo T, Peltoniemi M, Sievänen R (2005) Carbon and decomposition model Yasso for forest soils. Ecol Model 189:168–182
Liski J, Pussinen A, Pingoud K, Mäkipää R, Karjalainen T (2001) Which rotation length is favourable to carbon sequestration? Can J For Res 31:2004–2013
Liski J, Tuomi M, Rasinmäki J (2009) Yasso07 user-Interface manual. Finnish Environment Institute. http://en.ilmatieteenlaitos.fi/yasso-download-and-support. Accessed 20 Nov 2017
Liu G, Han S (2009) Long-term forest management and timely transfer of carbon into wood products help reduce atmospheric carbon. Ecol Model 220:1719–1723
Luyssaert S, Schulze E-D, Börner A, Khohl A, Hessenmöller D, Law BE, Ciais P, Grace J (2008) Old-growth forests as global carbon sinks. Nature 455:213–215
Malinen J, Kilpeläinen H, Piira T, Redsven V, Wall T, Nuutinen T (2007) Comparing model-based approaches with bucking simulation-based approach in the prediction of timber assortment recovery. Forestry 80(3):309–321
Mehtätalo L (2002) Valtakunnalliset puukohtaiset tukkivähennysmallit männylle, kuuselle, koivulle ja haavalle. Metsätieteen aikakauskirja 4:575–591
Morison J, Matthews R, Miller G, Perks M, Randle T, Vanguelova E, White M, Yamulki S (2012) Understanding the carbon and greenhouse gas balance of forests in Britain. In: Forestry Commission Research Report. Forestry Commission, Edinburgh. isbn:978-0-85538-855-3
Niinimäki S, Tahvonen O, Mäkelä A, Linkosalo T (2013) On the economics of Norway spruce stands and carbon storage. Can J For Res 43(7):637–648
Pihlainen S, Tahvonen O, Niinimäki S (2014) The economics of timber and bioenergy production and carbon storage in scots pine stands. Can J For Res 44:1091–1102
Pingoud K, Pohjola J, Valsta L (2010) Assessing the integrated climatic impacts of forestry and wood products. Silva Fenn 44(1):155–175
Pohjola J, Valsta L (2007) Carbon credits and management of scots pine and Norway spruce stands in Finland. Forest Policy Econ 9(7):789–798
Pukkala T (2006) Optimising the semi-continuous cover forestry of Finland. Allgemaine Forst und Jagdzeitung 1677:141–149
Pukkala T (2011) Optimising forest management in Finland with carbon subsidies and taxes. Forest Policy Econ 13:425–434

Pukkala T (2014) Does biofuel harvesting and continuous cover management increase carbon sequestration? Forest Policy Econ 43:41–50
Pukkala T (2017) Does management improve the carbon balance of forestry? Forestry 90(1):125–135. https://doi.org/10.1093/forestry/cpw043
Pukkala T, Lähde E, Laiho O (2009) Growth and yield models for uneven-sized forest stands in Finland. Forest Ecol Manag 258:207–216
Pukkala T, Lähde E, Laiho O (2013) Species interactions in the dynamics of even- and uneven-aged boreal forests. J Sustain Forest 32:1–33
Pukkala T, Lähde E, Laiho O, Salo K, Hotanen J-P (2011) A multifunctional comparison of even-aged and uneven-aged forest management in a boreal region. Can J For Res 41:851–862
Rantakari M, Lehtonen A, Linkosalo T, Tuomi M, Tamminen P, Heikkinen J, Liski J, Mäkipää R, Ilvesniemi H, Sievänen R (2012) The Yeasso07 soil carbon model – testing against repeated soil carbon inventory. Forest Ecol Manag 286:137–147
Repola J (2008) Biomass equations for birch in Finland. Silva Fenn 42(4):605–624
Repola J (2009) Biomass equations for scots pine and Norway spruce in Finland. Silva Fenn 43(4):625–647
Rummukainen A, Alanne H, Mikkonen E (1995) Wood procurement in the pressure of change – resource evaluation model till year 2010. Acta Forest Fenn 248:1–98
Russell MB, Fraver S, Aakala T, Gove JH, Woodall CW, D'Amato AW, Ducey MJ (2015) Quantifying carbon stores and decomposition in dead wood: a review. Forest Ecol Manag 350:107–128
Russell MB, Woodall CW, Fraver S, D'Amato AD, Domke GM, Skog KE (2014) Residence times and decay rates of downed woody debris biomass/ carbon in eastern US forests. Ecosystems 17:765–777. https://doi.org/10.1007/s10021-014-9757-5
Sathre R, O'Connor J (2010) Meta-analysis of greenhouse gas displacement factors of wood product substitution. Environ Sci Pol 13:104–114
Tuomi M, Laiho R, Repo A, Liski J (2011) Wood decomposition model for boreal forests. Ecol Model 222(3):709–718
Tuomi M, Thum T, Järvinen H, Fronzek S, Berg B, Harmon M, Trofymow JA, Sevanto S, Liski J (2009) Leaf litter decomposition – estimates of global variability based on Yasso07 model. Ecol Model 220:3362–3371
Zhou GY, Liu S, Li Z, Zhang D, Tang X, Zhou C, Yan J, Mo J (2006) Old-growth forests can accumulate carbon in soils. Science 314:1417
Zubizarreta-Gerendiain A, Pukkala T, Peltola H (2016) Effects of wood harvesting and utilization policies on the carbon balance of forestry under changing climate: a Finnish case study. Forest Policy Econ 62:168–176