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A simple method for detailed carbon calculations in forest management—with examples for planted larch

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Abstract Carbon sequestration is an important management objective in China's plantation forests, which are the most extensive in the world. Planning of plantation management often employs simulators that use either tree- or stand-level models. The use of individual-tree models is increasing in Heilongjiang Province, northeastern China, as these models enable flexible analyses of different stand structures, species compositions, and cutting types. So far, management optimization with individual-tree simulators has considered only the carbon storage of living tree biomass. This study proposed a method for expanding the simulators to accommodate the carbon storage of dead organic materials (DOM) and wood products. A dead tree is transferred to the dead-tree list, and a cut tree is transferred to the harvested tree list. Each new dead tree is characterized by the biomass of stem, branches, foliage, and roots, and the annual decomposition rate of each biomass component. A harvested tree is partitioned into harvest residue and wood product components. A residue component obtains biomass and the annual decomposition rate, and a wood product component obtains biomass and the yearly product disposal rate. From these lists, the remaining biomass of any DOM or product category can be easily computed for any future year. The method can be used in any country. In the example analyses conducted for Chinese larch (*Larix gmelinii*) plantations, the live tree carbon stock accounted for 75–80% of the total carbon storage, and wood products accounted for a maximum of 10–12%. Increasing the importance of carbon storage decreased cutting and led to longer rotations. Maximizing carbon storage as the sole objective resulted in very low harvest and long rotations (> 200 years).

Keywords Carbon sequestration · Carbon forestry · Forest management · *Larix gmelinii* · Simulation model

Introduction

The carbon sequestration of forests is an essential forest management objective in China and elsewhere (National Forestry and Grassland Administration 2021a; Heilongjiang Provincial Forestry and Grassland Bureau 2021). Wood production is also significant in plantation forests. Chinese forest policy statements also include several other management objectives, such as non-wood forest products and conserving ecological diversity (National Forestry and Grassland Administration 2021a, 2022).

China has the most extensive forest plantations in the world (National Forestry and Grassland Administration 2021b), meaning that the country's potential to sequester carbon from the atmosphere in forest ecosystems is high. Utilizing the carbon sequestration potential of the

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widespread plantations is essential for achieving China's carbon neutrality targets before 2060. Analyzing the relationship between wood production and carbon sequestration in plantation forests is an important question, as well as identifying management guidelines that would sequestrate carbon with minimal losses in wood production or produce wood with minimal losses to carbon sequestration.

Several studies accommodate both wood production and carbon sequestration objectives in management optimization. Studies in China and elsewhere suggest that timber production and carbon sequestration are strongly conflicting objectives (Jin et al. 2017; Pukkala 2018, 2020a; Tong et al. 2024). Several studies conducted in China consider only the carbon stock of live tree biomass (Jin et al. 2017; Peng et al. 2018; Song et al. 2023; Tong et al. 2025), which underestimates the total carbon sequestration potential of the forest ecosystem.

The carbon sequestrated in the photosynthesis of trees is stored directly or after mortality or logging into three carbon stores: (1) live trees, (2) dead organic material (DOM), and (3) wood products (Yang et al. 2013; Huang et al. 2016). Previous studies show that the DOM carbon store may have the same magnitude as the carbon store of live trees, at least at northern latitudes (Pukkala 2020b). The product pool is usually smaller (e.g., Rong et al. 2012; Díaz-Yáñez et al. 2019), but it can be enlarged by manufacturing durable wood products and using more wood in construction.

Maximizing carbon sequestration in forests without considering the carbon storage of wood products may lead to conclusions where cuttings are less than the true optimum. Partial cuttings release growing space for the remaining trees, and clear-felling makes space for a new tree generation. These may increase the rate at which carbon dioxide is removed from the atmosphere. Therefore, proper management optimization with the carbon sequestration objective needs to consider the carbon storage of wood products.

Management optimization that considers only the carbon stock of live trees may lead to shorter rotation lengths than optimizations that also consider the DOM pool. This is because the DOM carbon pool often increases towards older stand ages and continues to increase when the carbon pool of live trees no longer increases (e.g., Pukkala 2018). Some previous studies even suggest that the carbon storage of forests might be maximized if forests are not harvested at all (Pukkala 2020a). The inputs to the DOM pool consist of dead trees, harvest residues, and litter from live trees. Decomposition of DOM results in carbon outputs. The decomposition process may be simulated using decomposition simulators such as Yasso (Liski et al. 2005; Tuomi et al. 2011) and CO2FIX (Nabuurs et al. 2002; Kaipainen et al. 2004; Schelhaas et al. 2004), decomposition equations (Yatskov et al. 2003; Mäkinen et al. 2006), or fixed decomposition rate parameters (Shen et al. 1996; Wen et al. 2019; Zhu et al. 2023).

Conclusions about the effect of the carbon sequestration objective on cuttings depend on region and forest type. Therefore, results derived from a different climatic zone or a different type of forest cannot be generalized to Chinese tree plantations. For example, the DOM decomposes faster in warmer climates, which decreases its carbon storage capacity of forest soils. In addition, the conclusions are different for even-aged plantations and a multilayered forest that continuously gets new natural regeneration.

Stand development may be simulated using stand or tree-level models (Peng et al. 2018; Dong et al. 2022). Tree-level models are gaining popularity in China's plantation forests (e.g., Jin et al. 2017; Tong et al. 2024) since these models can be used easily in complex forest structures such as multilayered and mixed stands (Dong et al. 2025). Plantations often have regeneration of other species and shade-tolerant species are sometimes planted under the canopies of shade-intolerant plantation species. The dynamics of these stands are difficult to simulate with stand-level models. Stand-level models may also restrict the types of partial cuttings that can be simulated in management optimization (Pasalodos-Tato et al. 2010; Pukkala et al. 2014).

Northeast China may be the pioneer in using individual tree models in China. However, the southern subtropical plantation region is now another active area for the operational use of individual-tree models in forest management. They are used, for example, in Chinese fir (*Cunninghamia lanceolate* (Lamb.) Hook.) plantations (Zhao et al. 2013; Zhang et al. 2014; Lu et al. 2021; Jiang et al. 2022).

The objective of this study was to develop a method for calculating the carbon stocks of planted forests in individual-tree simulation, including three carbon stores: living tree biomass, dead organic materials, and wood products. This method can be used in any country for any plantation species. The main parameters are the decomposition rates of various DOM components and the half-lives of wood products. The required parameters can be obtained from literature or local experiments. The calculation method was implemented in a simulation–optimization tool that uses individual-tree models developed for planted larch forests (*Larix gmelinii*) in northeastern China. The developed method was used to analyze the trade-offs between carbon sequestration and wood production in larch plantations. The cuttings of planted stands were optimized using varying weights for wood production and carbon sequestration.

The carbon calculation method

The carbon calculation method suggested here assumes that forest dynamics are simulated with individual-tree models.

The simulator uses a list of live trees, where each entry represents either an individual tree or a diameter class. Our carbon calculation method adds two additional tree lists into the simulator, one for dead trees and the other for harvested trees. The third new component is the litter pool, which consists of sub-pools for branches, foliage, roots, and fine roots (root tips and roots thinner than 2 mm, Helmisaari et al. 2007). There is no stem litter pool because the stems of dead and harvested trees are dealt with at the tree-list level.

The growth of live trees is simulated using diameter growth models, and mortality is simulated using survivor functions (Tong et al. 2024) or mortality models (Dong et al. 2025). In most current simulators, the height increment is simulated by updating the tree height using static diameter-height curves (Jin et al. 2017; Peng et al. 2018; Tong et al. 2024). The volumes of different timber assortments are calculated by taper models (e.g., Peng et al. 2018), and biomass estimates are obtained from biomass equations, separately for stems, roots, branches, and foliage. Biomass equations are available for the main tree species of northeastern China (Dong et al. 2016). As an alternative to the stem biomass equation, the dry biomass of the stem can be calculated as the product of stem volume and the dry density of wood. The development of the carbon stock is obtained by multiplying the dry biomass by the carbon content of the biomass component, which is often near 0.5 (Fig. 1a).

Living trees produce litter, which is input to the carbon pool of dead organic material (DOM). In our method, the litter production from live trees is simulated using turnover rates, which is a commonly used method in carbon calculations (Liski et al. 2001; Pukkala 2020a). The turnover rate is the proportion of biomass shed as litter in 1 year. It is defined separately for branches, foliage, roots, and root tips. The turnover rates can be obtained from the literature (Zhang et al. 2008) or experiments. For foliage, they can be deducted from the life span of the leaves or needles.

The decomposition of litter components is simulated by using the annual decomposition rate (k) and the following equation (Olson 1963):

$$B_{t_2} = B_{t_1} e^{-k(t_2 - t_1)} \quad (1)$$

where B_{t_1} is the biomass in year t_1, B_{t_2} is the biomass t_2-t_1 years later, and k is the proportion of biomass that decomposes in one year. Using the turnover and decomposition rates, the dynamics of the litter pools can be easily simulated (Fig. 1c).

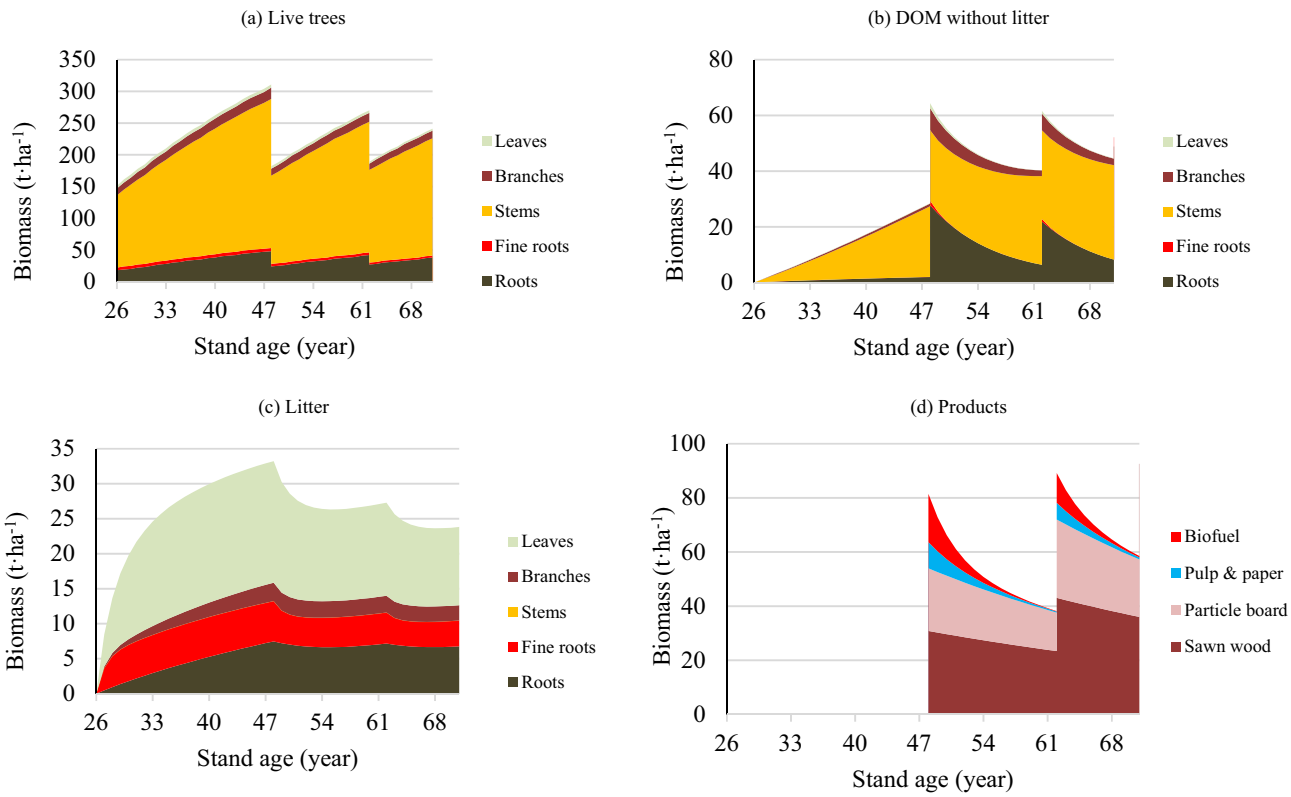

Fig. 1 Simulation example of the development of the biomass of live trees (**a**), dead organic material without litter (**b**), litter (**c**), and harvested wood products (**d**). The management schedule consists of two thinnings and a clear-felling. The simulation examples are for a 26-year-old *Larix gmelinii* plantation (Plot 2 in Table 5)

When a tree dies, it is moved to the dead tree list. The dead tree gets the following variables.

- Year of death
- Biomasses of the stem, branches, foliage, roots, and fine roots
- Decomposition rate of each biomass component

Assigning a decomposition rate to each dead tree enables the use of different decomposition rates for different tree sizes and species. The decomposition rate of the stem, especially, may depend on trunk diameter, large stems decomposing more slowly than small ones (e.g., Yatskov et al. 2003; Liski et al. 2005; Pukkala 2006). The remaining biomass of each dead tree in any future year can be calculated by using Eq. 1.

When a tree is harvested, it is moved to the list of harvested trees. Each harvested tree obtains the following parameters:

- Cutting year
- Biomasses of different product categories obtained from the tree (sawn wood, particle board, etc.)
- Disposal rate for each product category
- Biomasses of harvest residue components (treetop, branches, foliage, roots, fine roots)
- Decomposition rates for each biomass component of harvest residues

The stems of harvested trees are first divided into timber assortments by using a taper model, and each assortment is further divided into end-product categories (Fig. 2). The disposal rates of different products (Table 3) are related to their lifetimes (how long the product is used before discarding it). They can be obtained from the product half-lives reported for several types of wood products in Buendia et al. (2019), using the formula

$$k = -\ln(0.5)/L50 \quad (2)$$

where k is the annual disposal rate and $L50$ is the product half-life (number of years during which 50% of the product is discarded). Recycling can be considered in the calculation of k.

When each product and harvest residue category has received its biomass at the cutting moment and its annual disposal or decomposition rate, the remaining biomass of any component of the cut tree in any future year can be calculated using Eq. 1. Summing the biomasses of dead trees and harvest residues produces the size of the DOM pool without litter (Fig. 1b), and summing the remaining biomasses of the harvested trees' products produces the size of the wood product biomass pools (Fig. 1d). Summation of all DOM pools (litter, dead trees, harvest residues of cut trees) gives the total biomass of dead organic material present in the forest (Fig. 3).

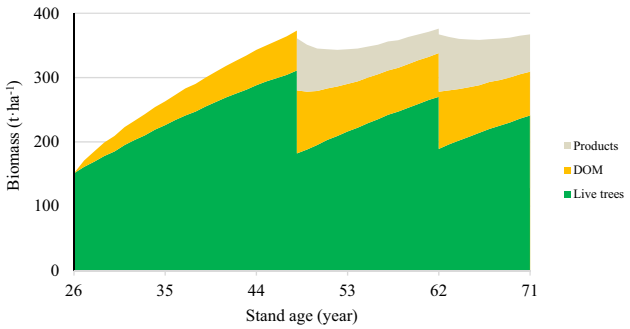

Fig. 3 Simulated development of the biomass of live trees, dead organic materials (DOM) and wood products in a larch plantation when the cutting schedule consists of two thinnings and a clear-felling. The simulation example is for a 26-year-old *Larix gmelinii* plantation (Plot 2 in Table 5)

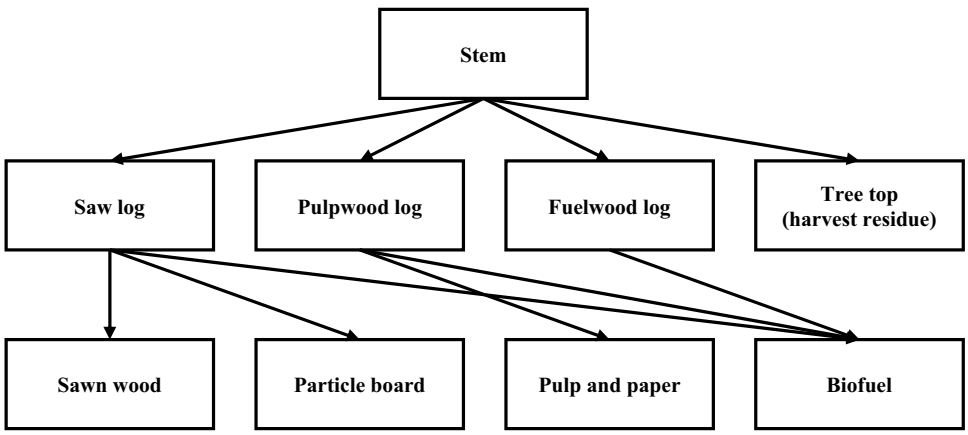

Fig. 2 The principle of partitioning the biomass of the stems of harvested trees across wood product categories. The treetops are harvest residues and remain in the forest

Simulations

The carbon calculation system described above was implemented in software that uses individual-tree models for larch (*Larix gmelinii*). The models used in the simulator are presented in the Appendix. The dominant height, diameter increment, and survival models were updated versions of models described in earlier research (Peng et al. 2018). The biomass of branches, needles and roots was calculated using biomass equations (Dong et al. 2016). The biomass of fine roots was assumed to be equal to foliage biomass (Vanninen and Mäkelä 1999; Helmisaari et al. 2007). In the examples used in this article, the stem biomass was calculated as the product of stem volume and wood density (0.53 t·m^3, Peng et al. 2020).

The turnover rates (Liski et al. 2006; Pukkala 2020a) shown in Table 1, were used to calculate the yearly litter production, and the decomposition rates in Table 1 were used to calculate the remaining biomass of dead trees and harvest residues. The parameters indicate, for example, that all larch needles are shed as litter once a year (turnover rate 1), and 35% of the needle litter biomass is lost in 1 year in the decomposition process (Zhang et al. 2008). Fine roots also decompose quickly (k = 0.98), which means that the size of the fine root DOM pool mainly depends on the new yearly litter input from the living trees.

The annual decomposition rate of the stems of dead trees was assumed to depend on breast height diameter (Tuomi et al. 2011). The model for parameter k in Eq. 1 (Table 1) was based on simulations with the Yasso decomposition model (Liski et al. 2005; Tuomi et al. 2011). Yasso is a global model that has been used in China (Gan et al. 2023) and elsewhere. The decomposition of larch stems of different diameters was simulated for 100 years, and the prediction model for k was fitted to the Yasso simulation results. The other parameters in Table 1 were obtained from the literature (Zhang et al. 2008; Tuomi et al. 2011; Wen et al. 2019; Zhu et al. 2023).

The timber assortments and wood products were assumed to be those shown in Table 2. A taper model (Appendix) was used to calculate the volumes of different assortments of harvested stems. If the length to the minimum top diameter was shorter than the minimum log length of the assortment, the volume was transferred to the next assortment (with a smaller minimum top diameter). For example, if the stem diameter was 24 cm at 3 m height and the 18 cm stem diameter was at 6 m height, the whole stem volume below 6 m height belonged to the medium-sized log. The calculation assumed that the preference order to crosscut different log types was: Large sawlog > Medium-sized sawlog > Small sawlog > Pulpwood log > Fuelwood log.

The assortment volumes were converted into biomasses using a wood density of 0.53 t·m^3, and the biomasses were distributed to different wood products using the proportions shown in Table 2. The biomass of the treetop (from 2 cm diameter to the tip) was included in the harvest residues, and

Table 1 Turnover rates and annual decomposition rates for biomass components. The turnover rate is the proportion of biomass shed annually as litter. The decomposition rate is the proportion of dead biomass that decomposes in 1 year. Symbol d is the diameter at breast height (cm)

Biomass component	Turnover rate	Decomposition rate (k)	References for the decomposition rate
Stem	0	$-3.256–0.302\ln(d)$	Tuomi et al. (2011)
Branches	0.02	0.12	Zhu et al. (2023)
Needles	1.00	0.35	Zhang et al. (2008)
Roots	0.02	0.12	Zhu et al. (2023)
Fine roots	0.7	0.98	Wen et al. (2019)

Table 2 Timber assortments and the proportions of wood products prepared from different assortments

	Large sawlog	Medium-sized sawlog	Small sawlog	Pulpwood log	Fuelwood log
Minimum top diameter, cm	24	18	12	6	2
Minimum piece length, m	4	4	4	2	1
Proportions of products					
Sawn wood	0.4	0.4	0.4	0	0
Particle board	0.3	0.3	0.3	0.0	0
Pulp and paper	0.1	0.1	0.1	0.5	0
Biofuel	0.2	0.2	0.2	0.5	1.0
Poles	0	0	0	0	0

it was added to the branch biomass of the harvested tree. It was assumed that the pulp and paper industry uses a chemical process where 50% of the biomass is converted into cellulose, and the remainder is used as biofuel (Pukkala 2011).

The developed carbon calculation system was used in three larch plots measured in the Mengjiagang forest farm in Heilongjiang Province in northeastern China (Table 4). The site indices of the plots were 20, 22, and 24 m. The site index was defined as the dominant height at 30 years. The simulator was linked with an optimization algorithm to find the optimal management of the stand when wood production or carbon sequestration was maximized or when both management objectives were pursued simultaneously.

The optimization maximized the following utility function.

$$U = w_1\left(WP/WP_{max}\right) + w_2\left(CS/CS_{max}\right) \quad (3)$$

where U is the utility index computed for the cutting schedule, WP is the mean annual harvest ($m^3ha^{-1}a^{-1}$), CS is the average total carbon stock of the three carbon pools (live trees, DOM, wood products) during the rotation, w_1 is the weight of the wood production objective and w_2 is the weight of the carbon storage objective ($w_1 + w_2 = 1$). The carbon pool was obtained by multiplying the biomass pool by 0.5. WP_{max} is the maximum possible wood production, and CS_{max} is the maximum possible average carbon stock during rotation. They were obtained in preliminary optimizations that maximized WP or CS as the only objective.

Maximizing Eq. 3 with different weight combinations produced tradeoff information, which was visualized by tradeoff curves. The curves showed the effect of increasing carbon storage on wood production, or vice versa. The development of carbon stock under the optimal cutting schedule was reported for the following cases: (1) $w_1 = 1$ (wood production maximized), (2) $w_1 = w_2 = 0.5$, and (3) $w_2 = 1$ (carbon stock maximized). Based on earlier research, it was assumed that two thinning treatments during the rotation were suitable for planted larch (Peng et al. 2018).

Additional analyses were conducted for site index 22, assuming that poles are a fifth wood product type. Poles can be prepared from different stem sizes (fence poles, telecommunication poles, etc.), and most of the stem volume, biomass and carbon can be transferred to the product. In sawmills, only about 50% of the biomass and carbon of the log passes to sawn wood (Hurmekoski et al. 2023). The remaining carbon often goes to short-lived products such as pulp and biofuel. Poles can be good carbon stores, especially when impregnated. This additional analysis assumed that pulp and paper, which are poor carbon stores, are not made. The product half-life of poles was 35 years, which corresponds to a yearly disposal rate (k) of 0.0198.

The simulation started with young pre-commercial larch plots (Table 5). When calculating the average carbon stock of the rotation, it was assumed that the biomass of live trees increases linearly from zero to the biomass of the plot at the start of the simulation. The optimization method was differential evolution, which was used in the same way as explained in Tong et al. (2024). The problem formulation was similar to that in Tong et al. (2024).

Table 3 The half-lives and disposal rates for different product types. Half-life is the number of years during which 50% of the product is discarded (Buendia et al. 2019)

Product type	Half-life (years)	Disposal rate (k)
Sawn wood	35	0.0198
Particle board	20	0.0346
Pulp and paper	3	0.231
Biofuel	3	0.347
Poles	35	0.0198

Case study results

Trade-off curves

The tradeoff curves indicated that wood production (the mean annual harvest) and carbon sequestration were conflicting objectives (Fig. 4). When maximizing carbon sequestration instead of wood production, the mean annual harvest decreased from 6.5 to about 1.5 $m^3ha^{-1}a^{-1}$ in site index 20 m and from 11 to about 2 $m^3ha^{-1}a^{-1}$ in site index 24 m. The maximal carbon stock did not lead to zero-harvest, implying that harvesting can

Table 4 Proportions of wood products prepared from different assortments in the analysis, assuming that wood is not used for pulp and paper, and a substantial proportion of stems is used as poles

	Large sawlog	Medium-sized sawlog	Small sawlog	Pulpwood log	Fuelwood log
Proportions of products					
Sawn wood	0.3	0.3	0.3	0	0
Particleboard	0.15	0.15	0.15	0	0
Pulp and paper	0	0	0	0	0
Biofuel	0.15	0.15	0.15	0	1.0
Poles	0.4	0.4	0.4	1.0	0

Table 5 Information on the plots used in the calculations

Variables	Plot 1	Plot 2	Plot 3
Site index, m	20	22	24
Age, a	27	26	26
Dominant height, m	18.4	20.0	22.2
Number of trees per ha	1230	1833	1756
Basal area, m^2 ha^{-1}	17	26	26
Mean diameter, cm	13.4	13.3	13.8
Minimum diameter, cm	5.5	6.3	7.0
Maximum diameter, cm	21.4	23.5	23.4

improve the carbon sequestration of forests. However, when high carbon storage is targeted, harvesting should be greatly decreased from the maximum possible removals.

Most of the sequestrated carbon was in the biomass of living trees (Fig. 4, dotted blue line). DOM was the second-largest carbon store. Compared to live trees and DOM, the carbon storage of wood products was small. Its share of the total carbon stock was the largest (10–12%) when wood production was maximized.

Optimization examples

Maximizing forest management with increasing importance of carbon sequestration increased the rotation lengths in both site indices (Fig. 5). When the weight of the carbon sequestration objective was 0.5 ($w_2 = 0.5$ in Eq. 3), the thinning treatments were postponed compared to schedules that maximized wood production. In the poorer site (SI = 20 m), there was only one late thinning, and in the better site (SI = 24 m), the second thinning removed only a few trees. Postponed thinning and longer rotation length increased the average carbon stock of the living trees from 51 to 99 $t{\cdot}ha^{-1}$ in SI 20 m and from 69 to 108 $t{\cdot}ha^{-1}$ in SI 24 m (Table 6). The total carbon stock (live trees + DOM + products) increased from 62 to 123 $t{\cdot}ha^{-1}$ in SI 20 m and from 88 to 141 $t{\cdot}ha^{-1}$ in SI 24 m.

When the weight of carbon storage increased from 0 to 0.5, wood production decreased from 6.6 to 5.4 $m^3ha^{-1}a^{-1}$ in SI 20 m and from 11.0 to 9.5 $m^3ha^{-1}a^{-1}$ in SI 24 m (Table 6). Therefore, large increments in the average carbon storage of forests and wood products were achieved with reasonably small reductions in wood production. The harvests of large logs, the most valuable timber assortment, increased in both sites when wood production and carbon sequestration were maximized simultaneously. When wood production was maximized, the carbon stock of wood products was of the same magnitude as the DOM carbon stock (Table 6). Maximizing both wood production and carbon stock with equal weights decreased the product carbon stock by 14–16%, but the sizes of the DOM and live tree carbon stocks were doubled.

Maximizing carbon sequestration as the only objective resulted in very long rotations and no-thinning management schedules (Fig. 5). The rotations were about two times longer than the age at which the carbon stock of living tree biomass achieved its highest value. The carbon stock of DOM continued to increase beyond this age because of the mortality of large trees, the stems of which decompose slowly.

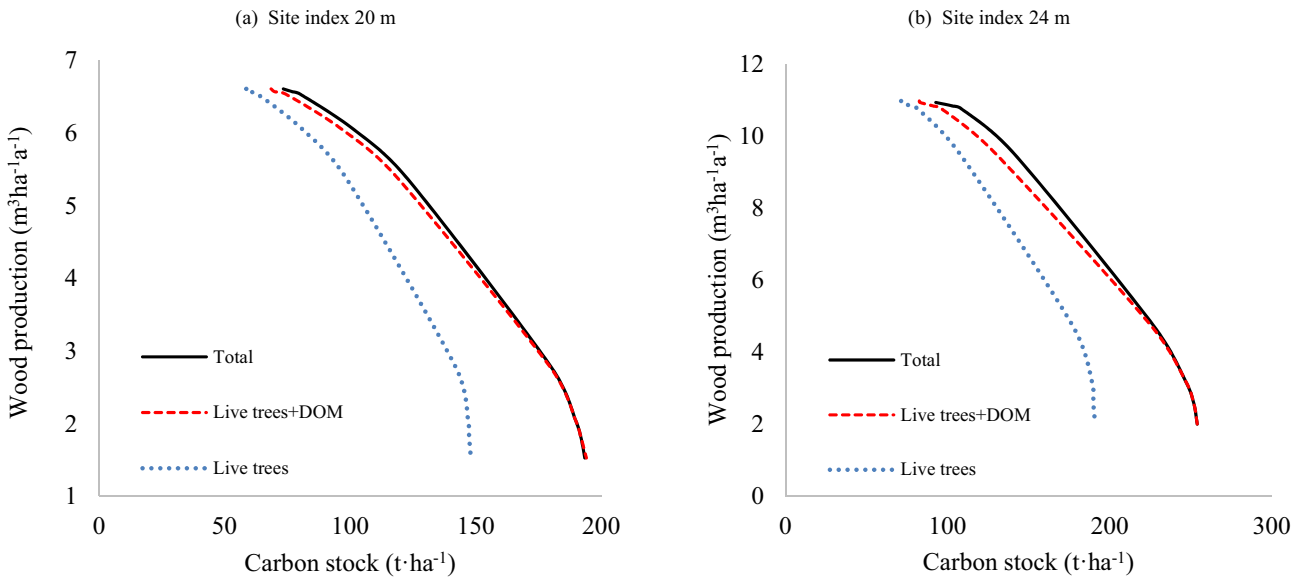

Fig. 4 Tradeoff curves (black continuous lines) between wood production (mean annual harvest) and the average total carbon stock of the rotation (Live trees + DOM + wood products). The dotted blue lines show the carbon stock of live trees, and the dashed red lines show the carbon stock of live trees and DOM

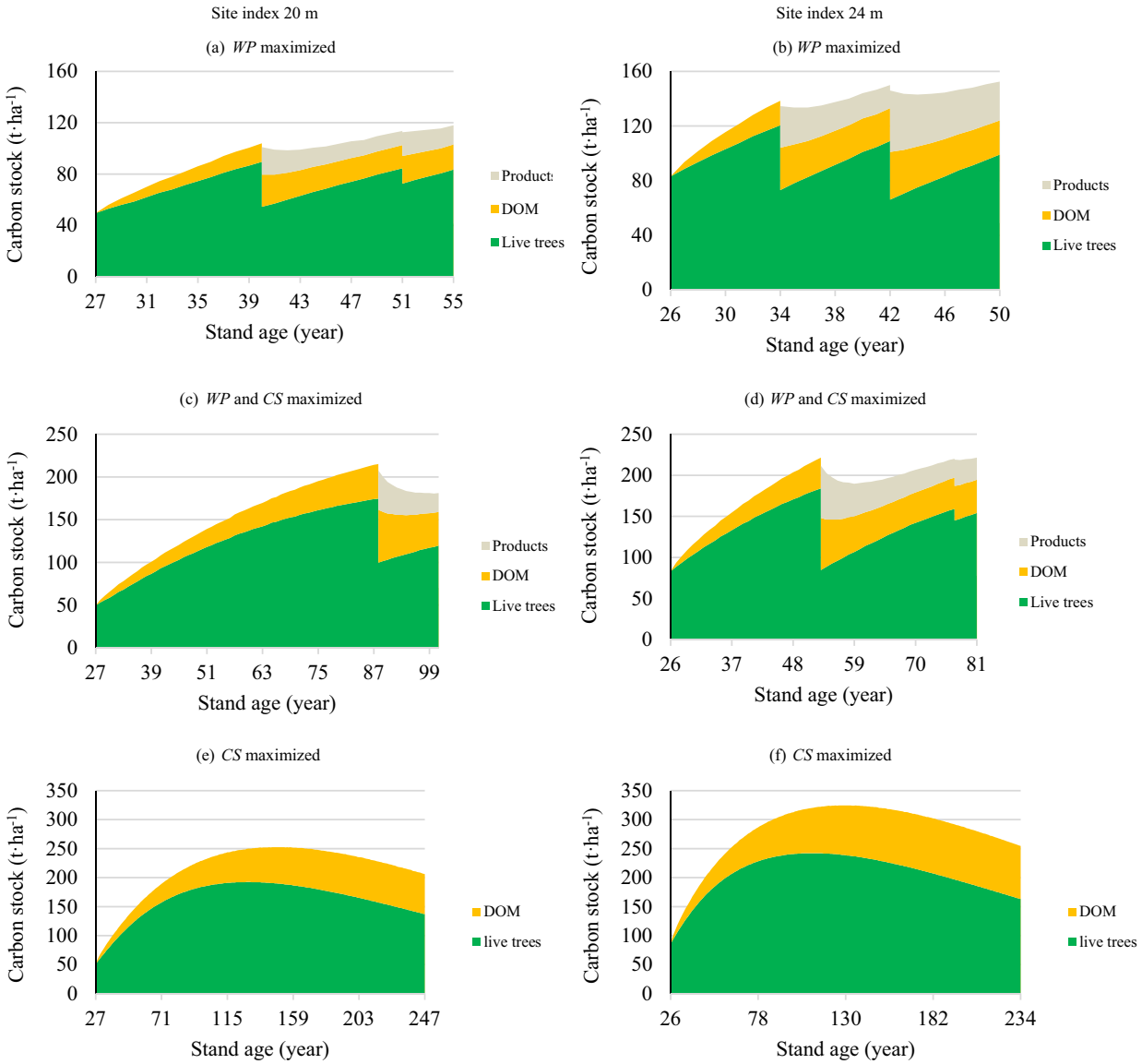

Fig. 5 Development of carbon stocks in the optimal management schedule in site index 20 m (left column) and 24 m (right column) when wood production, WP, (**a**, **b**) or average carbon stock of the rotation, CS, (**e**, **f**) or both WP and (**c**, **d**) are maximized

Maximizing plantation management with all weight on carbon sequestration did not result in no-cutting management. Optimal management advised to clear-fell the stand when the carbon stock of the live tree and DOM pools was equal to the average carbon stock of the rotation. This is a logical result since continuing the rotation beyond this year would decrease the mean carbon stock of the stand during the rotation.

Maximizing carbon storage decreased harvest from 6.6 to 1.5 $m^3ha^{-1}a^{-1}$ in SI 20 m, and from 11 to 2 $m^3ha^{-1}a^{-1}$ in SI 24 m compared to the schedule that maximized wood production (Table 6). The harvests of large sawlogs increased but were less than in the schedule where both management objectives were simultaneously maximized.

The biomass of trees harvested in clear-felling was transferred either to the DOM (harvest residues) or product pools. These pools will be the initial carbon pools of a new plantation. The post-clear-felling product pools were of the same magnitude in all three schedules and for both site indices (Fig. 6a). Therefore, none of the schedules offered significant advantages over the others in terms of the product pool size at the beginning of the new rotation.

There were significant differences in the size of the post-clear-felling DOM pools (Fig. 6b), with the Max C schedule being superior to the other schedules. When the clear-felled area is planted again, the initial DOM pool of a new plantation was 2.5–3 times larger for the Max C schedule compared to the Max WP schedule. Since most of the biomass

Table 6 Mean annual wood production, average carbon stocks, and rotation length when wood production (Max WP), carbon sequestration (Max CS), or both (50:50) were maximized

Site index		Wood production (m^3 ha^{-1} a^{-1})	Large log production (m^3 ha^{-1} a^{-1})	Average total carbon stock (t ha^{-1})	Live tree carbon stock (t ha^{-1})	DOM carbon stock (t ha^{-1})	Product carbon stock (t ha^{-1})	Rotation length (year)
Site index 20 m	Max WP	6.6	0	61.8	50.2	7.7	3.9	55
	50:50	5.4	2.4	122.9	98.6	20.6	3.7	101
	Max CS	1.5	1.3	193.4	147	46.4	0	247
Site index 24 m	Max WP	11	0	87.9	68.6	10.5	8.8	52
	50:50	9.5	2.1	140.9	107.4	22.2	11.3	74
	Max CS	2	1.7	253.8	188.1	65.8	0	234

and carbon are in roots and stems, which decompose relatively slowly, the higher carbon stock of the Max C schedule would last longer, even if the management of the next rotation was similar in both cases.

The pole production case

The results of the previous sections indicated that the carbon pool of wood products was only 0–12.5% of the total carbon storage, depending on site productivity and management objective. The small share is partly because some products (especially pulp, paper, and biofuel) are not durable carbon stores. When sawlogs are sawn, only about 50% of the carbon in sawlogs is transferred to sawn wood, which means that sawlog is not an ideal assortment in carbon forestry either.

If the stems were used as durable poles, a greater proportion of the stem carbon could be stored in products. An analysis on the effect of pole production in site index 22 m revealed, however, the effect of this change on the carbon storage was small (Fig. 7), although a substantial proportion of harvested wood was used as poles (Table 4) and the life span of poles was assumed to be the same as with sawn wood (product half-life 35 years). The pole product category had no major effect on the optimal management schedule (Fig. 7). When the carbon storage of forests and products was maximized, the optimal management did not include thinning, and the rotation length was the same (241 years) both with and without the pole product category.

Almost half of the product carbon pool after clear-felling was in the poles (Figs. 8b and 9). The size of all other product carbon pools decreased when poles were made. Although poles did not have much effect on optimal forest management or average carbon storage of the rotation, the product carbon pools immediately after clear-felling differed significantly for the no-poles and poles cases (Fig. 9). The total product pool was larger when poles were made. However, the most significant difference was in the composition of the product pools. The most durable pools were poles and sawn wood, the total size of which almost doubled when pools were made. Since these pools exist when the clear-felled area is planted again, the benefit of the pole product category would continue beyond the clear-felling year.

Discussion

Analysis of the method

The carbon calculation method described in this article is easy to implement in individual tree simulators. The method can be used in any country for any species for which individual-tree growth models, biomass models, and parameters for the carbon dynamics are available. The carbon parameters are set separately for each species, based on available research (Wen et al. 2019; Zhu et al. 2023), expert knowledge, existing models (Tuomi et al. 2011), or biological properties of the species. For example, if the species is evergreen and the average life span of its needles or leaves is 3 years, around a third of the foliage is shed annually as litter, resulting in a turnover rate of 0.33.

The typical half-lives of different wood product types can be found in the literature (e.g., Buendia et al. 2019). The product half-life can be converted into annual rates of product disposal. If the discarded product is recycled, which lengthens the carbon storage, this can be considered in the disposal rate. As the product disposal rates depend on human decisions, there is no single correct value for carbon calculations. The disposal rates are assumptions about future decisions. Our method makes it easy to analyze the effect of increased recycling or more durable products on the carbon sequestration of forests.

For the carbon calculations described in this article, the individual-tree simulator is augmented with two tree lists, one for dead trees and the other for harvested trees. The tree is moved from the living tree list to one of the other lists when the tree dies or is cut. A dead or cut tree gets the biomass and decomposition/disposal rates of the biomass

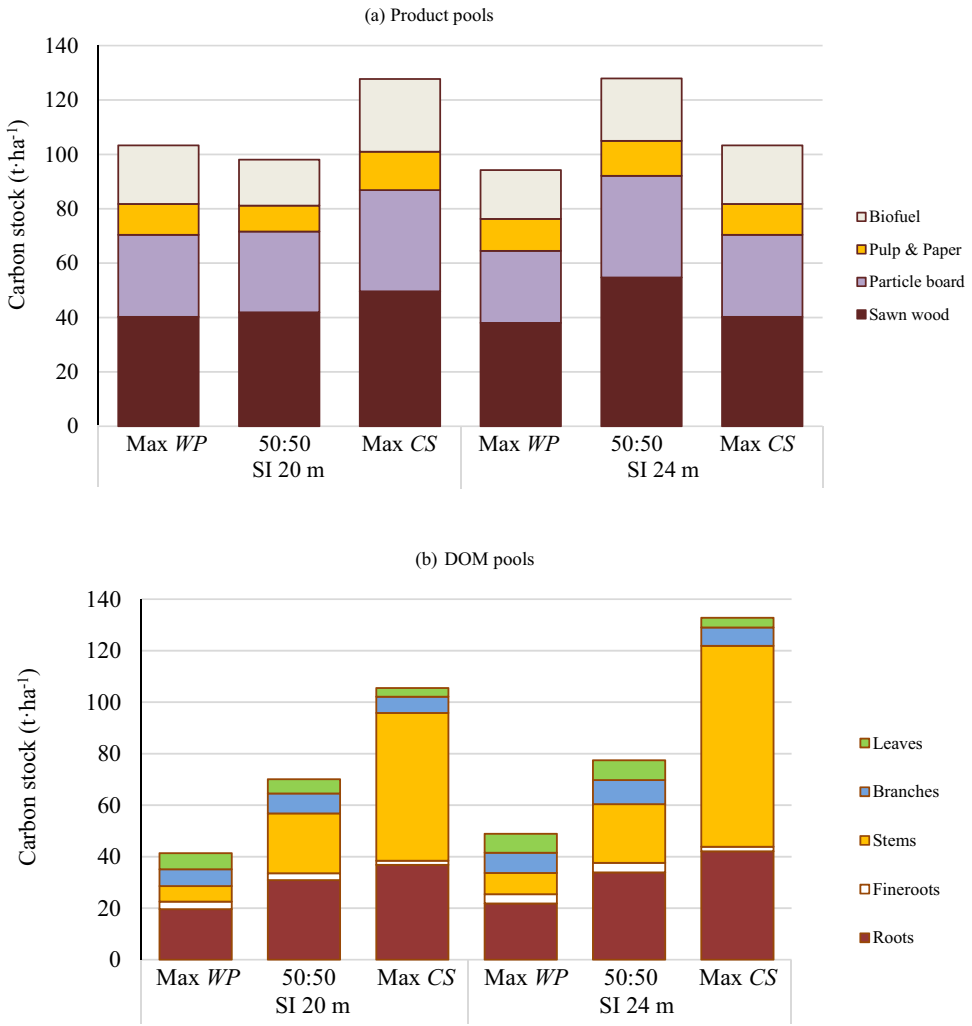

Fig. 6 Size of the product (**a**) and DOM carbon pools immediately after clear-felling for two site indices (20 m and 24 m) and three different weights of the wood production and carbon storage objectives (Eq. 3). Max WP: $w_1 = 1$, $w_2 = 0$; 50:50: $w_1 = w_2 = 0.5$; Max C: $w_1 = 0$, $w_2 = 1$

components. There is no need to simulate the decomposition of dead trees or the disposal of harvested wood products since the remaining biomass and carbon can be calculated for any future year using the initial biomass and the decomposition or disposal parameter (k in Eq. 1).

Despite its simplicity, the method produces detailed information. The method can also be used in ecological analyses. For example, the amount of deadwood in different diameter classes can be calculated by a summation over the dead-tree list. The stems of dead trees can be classified into different categories based on the stage of decomposition to evaluate the suitability of the stand for various saproxylic species (Zubizarreta et al. 2019). The stems of dead trees provide habitats for several species, depending on the species, size, and stage of decomposition (Tikkanen et al. 2007).

Simulating the carbon dynamics of litter was based on turnover and decomposition rates. The same method has been used in previous studies (Liski et al. 2001; Peltoniemi et al. 2004; Pukkala 2014). The annual litter yield mainly consists of short-lived biomass components such as foliage, twigs, root tips, and other small roots. The biomass and carbon content of the litter may be substantial, but the litter pool quickly reaches a near-stable state where the input (yearly litter addition) is equal to the output (decomposition). Therefore, the litter pool cannot be increased much by letting the forest grow older. As the size of the litter pool is closely related to the annual litter input, it reaches its maximum at the same time as the biomass of living trees. Partial cuttings decrease the litter pool because litter input decreases.

The vegetation of forests also includes herbs, grasses, mosses, dwarf shrubs, and bushes. They grow, die and decompose, affecting both the carbon balance and carbon stock of the forest. However, compared to trees, the carbon pool of this vegetation is small, and it often reaches a steady state where the decomposition of dead plants is nearly the same as the biomass growth. Therefore, ignoring vegetation other than trees does not significantly bias the results of the method suggested in this study.

In the calculation examples of this study, the initial sizes of the product and DOM pools were zero. The carbon pool

of living trees was assumed to grow linearly from zero to the pool size of the stand at the start of the simulation. These simplifications did not influence the optimization results because they had no effect on the differences between the management schedules examined. However, the sizes of the litter and DOM pools were underestimates for the first simulation years because litter and other DOM inputs before the initial stand age were ignored.

If trees are planted on clear-felling sites, the site has DOM and product carbon stocks also from previous rotations. They could be considered by initializing the pools with the sizes of the post-clear-felling pools of the previous rotation. If the plantation is established on bare land or for replacing degraded vegetation, initialization from the previous rotation is not necessary. Using the ending carbon stock of the previous rotation as the initial pools of a new rotation is recommended when the plantations are clear-felled and replanted.

When carbon calculations are made for current forests, the calculations seldom begin from the planting year. Therefore, there is a need to develop predictive initialization models for the sizes of the DOM and product pools at different

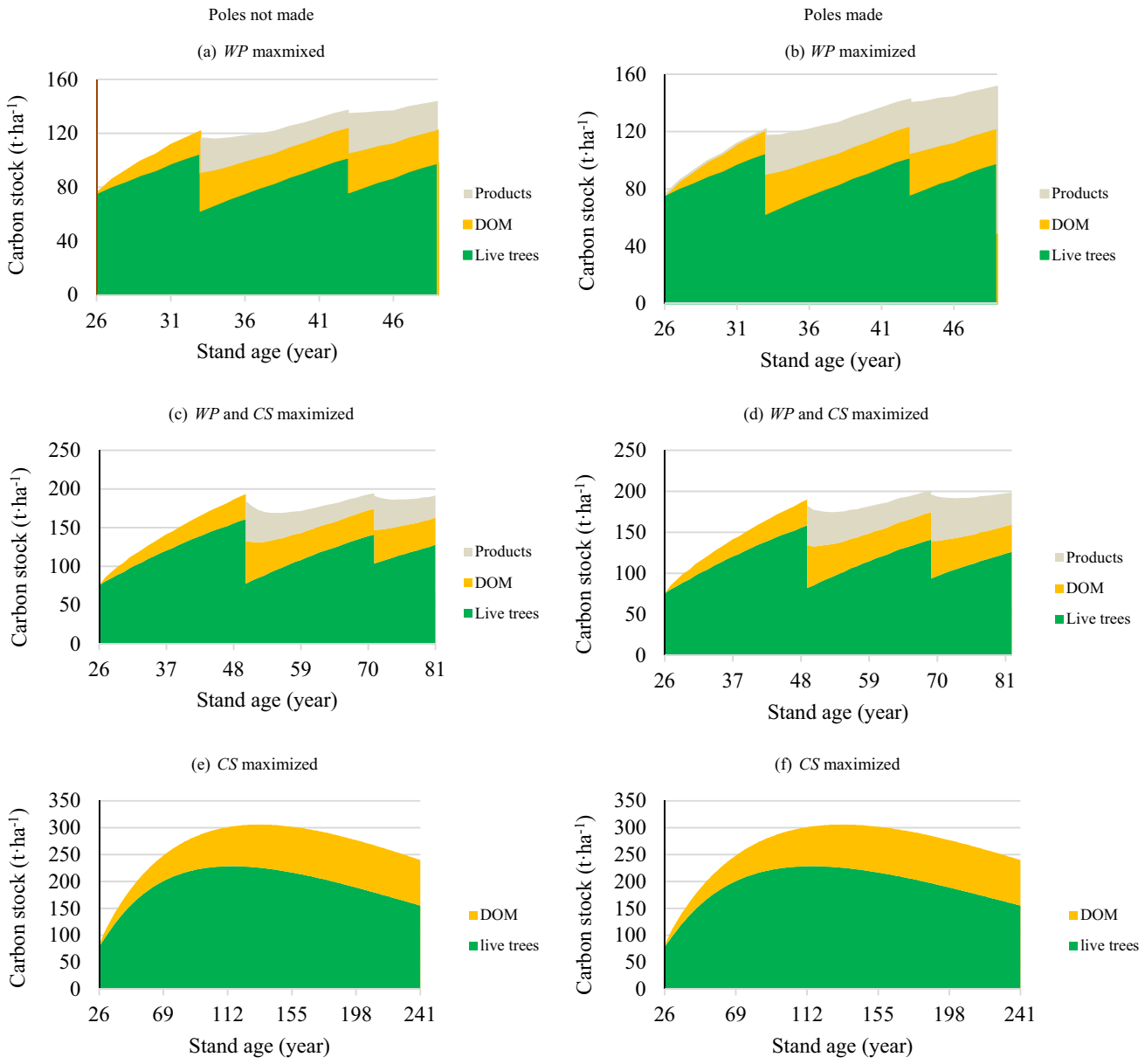

Fig. 7 Development of carbon stocks in the optimal management schedule for site index 22 when wood production (WP) (**a**, **b**), average carbon stock of the rotation (CS) (**e**, **f**), or both WP and CS (**c**, **d**) are maximized, and the wood products do not (left panel) or do (right panel) include poles

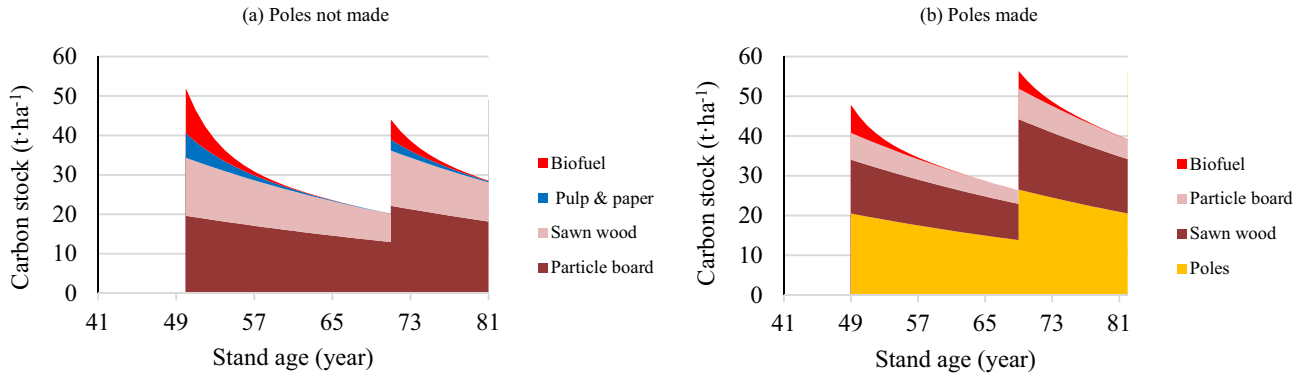

Fig. 8 Development of the product carbon pool when the management was optimized in site index 22 m with equal weights on wood production and carbon storage, without and with the pole product category

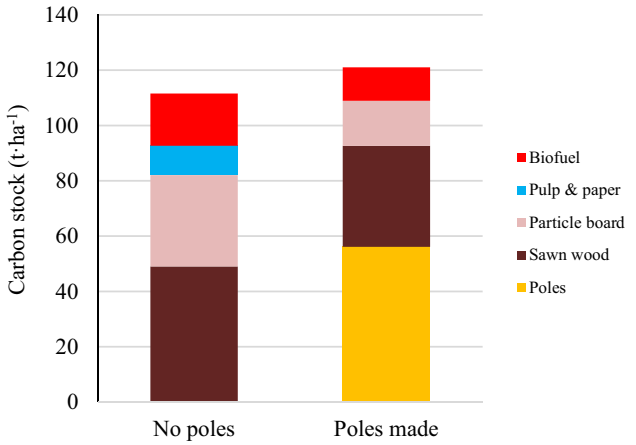

Fig. 9 Product carbon pools after clear-felling in site index 22 m when poles are (right) or are not made (left). The results are for optimization where the weights of wood production and carbon sequestration are equal ($w_1 = w_2 = 0.5$ in Eq. 3)

stand ages (Pukkala 2020b). The methodology described in the article can be used to produce simulated data for these models.

Using the average carbon stock of the rotation as the objective is justified, as increased carbon stocks of forests and wood products mean that carbon is sequestered from the atmosphere. Carbon is permanently sequestrated only if the carbon stores of live trees, DOM and products are enlarged and kept at the enlarged level. Climate warming depends on the amount of carbon dioxide in the atmosphere, not on the rate at which it is sequestrated in photosynthesis. The larger the carbon stocks of trees, DOM and wood products, the more carbon is kept away from the atmosphere.

Analysis of the case study results

The optimization results showed that the carbon storage objective increased rotation lengths and decreased wood production, which agrees with the results of Dong et al. (2020). When wood production and carbon storage were equally important, wood production was 14–18% smaller than the maximal wood production, but the total carbon storage of trees, DOM and products increased by 60–99%. Moreover, the production of the most valuable timber assortment increased. Therefore, significant improvements in carbon storage can be achieved with reasonably small losses in timber production.

The result that increased carbon sequestration decreases cutting agrees with many earlier studies (Van Kooten et al. 1995; Liski et al. 2001; Guthrie and Kumareswan 2009; Raymer et al. 2011; Heinonen et al. 2017; Assmuth and Tahvonen 2018). Our analysis of the pole product category showed that this conclusion does not change if more durable products are manufactured. However, in the longer term, when the analysis extends over several rotations, more durable products would increase carbon storage. On the other hand, the increase would last only for the time when the sizes of the product carbon pools are increasing. If the production of poles and other durable products does not increase, the pool size will stabilize, because product disposal will eventually be equal to the product manufacturing.

Maximizing carbon storage did not lead to no-cutting prescriptions, but partial cuttings ceased. The analyses showed that the stand was to be clear-cut and planted again when the size of the carbon stock of trees and DOM was equal to the average size of the forest carbon pool during the rotation. Additional growing years would decrease the average carbon stock of the rotation. The optimal rotation lengths were much longer than the rotation lengths that maximize wood production (Peng et al. 2018). On the other hand, the natural lifespan of larch is 250–400 years (Zhang 2008), which means that our optimization results are not unfeasible biologically.

The conclusion that maximal carbon storage does not lead to no-cutting might change when there is natural regeneration in the forest. In this situation, it may be optimal to stop all harvesting (Pukkala 2020b), depending on how quickly the stand gets natural regeneration and how fast the regeneration grows. This outcome would be more likely if large dead trees are better carbon stores than wood products (Pukkala 2018). The likelihood of no-cutting being optimal for carbon storage can be decreased by decreasing the use of wood for bioenergy and short-lived products such as paper and packaging materials.

The substitution effects of wood products and biofuel may change the conclusion in favor of cutting. On the other hand, the substitution effects are expected to decrease in the future because the materials and energy sources that compete with wood are gradually decarbonized (Hurmekoski et al. 2020).

Conclusions

The article describes a straightforward and detailed method for simulating the carbon dynamics of tree plantations. The method can be implemented in simulators that use individual-tree models to predict tree growth and survival. The method needs predictive models or expansion factors for estimating the biomass of stems, branches, foliage, and roots. The main advantage of the method is that external models, such as Yasso or CO2FIX, are not needed. The calculation system is easy to update, maintain, and expand to other species, because only the parameters for the carbon dynamics need to be modified. The method provides detailed information that can also be used beyond carbon accounting, for instance, in ecological analyses. The case study results for planted *Larix gmelinii* suggested that maximal carbon sequestration leads to no-thinning management and long rotation lengths.

Author contributions Bo Jiang: formal analysis, writing—original draft, visualization. Xingji Jin: conceptualization, formal analysis, writing—review and editing, data curation, supervision, project administration. Timo Pukkala: conceptualization, methodology, software, formal analysis, writing—original draft, visualization, supervision. Weifang Wang: data curation, writing—review and editing, funding acquisition.

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Data availability The authors do not have permission to share data.

Declarations

Conflict of interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix: Models used in simulation

Repeated measurements from 564 sample plots were used to obtain 1250 pairs of age and dominant height. They were used to fit a GADA (Generalized Algebraic Difference Approach) model derived from the Richards (1959) equation:

$$L_0 = \ln\left(1 - e^{-0.0804 t_0}\right) \tag{4}$$

$$X_0 = \frac{1}{2}\left(\left(\ln\left(\mathrm{HD}_0\right) + 2.380 L_0\right) + \sqrt{\left(\ln\left(\mathrm{HD}_0\right) + 2.380 L_0\right)^2 - 61.500 L_0}\right) \tag{5}$$

$$HD = HD_0 \left(\frac{1 - e^{-0.0804 t}}{1 - e^{-0.0804 t_0}}\right)^{-2.380 + \frac{15.375}{X_0}} \tag{6}$$

where HD represents dominant height (m) and t denotes stand age (years). The site index (SI) of the plots was calculated by substituting t_0 with the reference age (30 years), t with the stand age, and HD_0 with the observed dominant height.

The height-diameter curve model is based on 344 repeated measurements from 203 sample plots, encompassing 38229 sample trees. The model is:

$$h = 1.3 + (-48.953 + 14.555 \ln(T) + 1.130 SI) \exp\left[\frac{-(-15.994 + 5.313 \ln(T) + 0.196 SI)}{d}\right] \tag{7}$$

where T is the stand age (years), SI is the site index (m at reference age), and d is the diameter of the tree at breast height (cm).

The diameter increment and survival models are based on the same plots as the height model. The models were fitted simultaneously using the optimization method of Pukkala et al. (2011):

$$i_{\mathrm{d}} = \exp\left(-3.183 + 0.0212d - 0.00146d^2 - 0.109\ln G + 0.905\ln SI - 0.123\frac{BAL}{\ln(d+1)} + 0.601\left(1 - \frac{BAL}{G}\right)\right) \quad (8)$$

$$s = \frac{1}{1 + \exp\left[-\left(-0.00996 + 2.133\ln d - 0.0979d - 0.0751\frac{BAL}{\ln(d+1)} + 4.513\left(1 - \frac{BAL}{G}\right)\right)\right]} \quad (9)$$

where i_{d} is the annual diameter increment (cm a^{-1}), s is the annual survival rate probability of survival) d is the diameter at breast height (cm), G is the stand basal area (m^2 ha^{-1}), BAL is the the basal area of larger trees (m^2 ha^{-1}), and SI is the site index (m).

The taper model was as follows:

$$d = 0.9314728D^{0.985}H^{0.0419}x0.5106q^4 - 0.542\left[\frac{1}{\exp\left(\frac{D}{H}\right)}\right] + 0.478x^{0.1} + 1.187\left(\frac{1}{D}\right) + 0.0192H^{1-q^{\frac{1}{3}}} - 0.0962x \quad (10)$$

where d is the diameter (cm) at height h, D is the diameter at breast height (cm), H is the total height of the tree (m), $x = (1 - q^{1/3})/(1 - t^{1/3})$, $q = h/H$, and $t = 1.3/H$.

The following models (Dong et al. 2016) were used to calculate the biomasses of branches, foliage and roots:

$$B_{branch} = 0.024075d^{2.1147} \quad (11)$$

$$B_{foliage} = 0.098411d^{1.2549} \quad (12)$$

$$B_{root} = 0.004743d^{2.9914} \quad (13)$$

where d is the diameter at breast height (cm). The stem biomass was calculated as a product of stem volume and dry density of wood (0.53 t·m^3).

References

Assmuth A, Tahvonen O (2018) Optimal carbon storage in even- and uneven-aged forestry. For Policy Econ 87:93–100. https://doi.org/10.1016/j.forpol.2017.09.004

Buendia E, Tanabe K, Kranjc A, Baasansuren J, Fukuda M, Ngarize S, Osako A, Pyrozhenko Y, Shermanau P, Federici S (2019) Refinement to the 2006 IPCC guidelines for national greenhouse gas inventories; intergovernmental panel on climate change: geneva, Switzerland

Díaz-Yáñez O, Pukkala T, Packalen P, Peltola H (2019) Multifunctional comparison of different management strategies in boreal forests. Forestry 93(1):84–95. https://doi.org/10.1093/forestry/cpz053

Dong LH, Zhang LJ, Li FR (2016) Developing two additive biomass equations for three coniferous plantation species in Northeast China. Forests 7(7):136. https://doi.org/10.3390/f7070136

Dong LB, Lu W, Liu ZG (2020) Determining the optimal rotations of larch plantations when multiple carbon pools and wood products are valued. For Ecol Manag 474:118356. https://doi.org/10.1016/j.foreco.2020.118356

Dong LB, Bettinger P, Qin HY, Liu ZG (2022) Optimizing rotation lengths for maximizing carbon balance of larch plantations in northeast China. J Clean Prod 343:131025. https://doi.org/10.1016/j.jclepro.2022.131025

Dong LH, Wang Q, Jin XJ, Pukkala T, Li FR (2025) Productivity of mixed plantations of ash and larch in northeastern China -a model-based analysis. For Ecol Manag 585:122609. https://doi.org/10.1016/j.foreco.2025.122609

National forestry and grassland administration (2021a) National guidelines for the development of under-forest economy (2021–2030) [Report]. https://www.forestry.gov.cn/

National forestry and grassland administration (2021b) Comprehensive monitoring and assessment report on forest and grassland ecology in China. [Report]. https://www.forestry.gov.cn/

National forestry and grassland administration (2022) Development plan for forestry and grassland industries (2021–2025) [Report]. https://www.forestry.gov.cn.

Gan XF, Guo BQ, Ma ZM, Fang MJ, Yan Y, Liu WG (2023) The effect of forest growth rate on climate change impacts of logging residues utilization. Atmosphere 14(8):1270. https://doi.org/10.3390/atmos14081270

Guthrie G, Kumareswan D (2009) Carbon subsidies, taxes and optimal forest management. Environ Resource Econ 43:275–293. https://doi.org/10.1007/s10640-008-9238-4

Heilongjiang provincial forestry and grassland bureau (2021) 14th five-year plan for forestry and grassland protection and development in Heilongjiang Province [Report]. http://lyhcyj.hlj.gov.cn/lyhcyj/c107253/202110/30886007/files/1634780515074015448.pdf

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. For Policy Econ 80:80–98. https://doi.org/10.1016/j.forpol.2017.03.011

Helmisaari HS, Derome J, Nöjd P, Kukkola M (2007) Fine root biomass in relation to site and stand characteristics in Norway spruce and Scots pine stands. Tree Physiol 27(10):1493–1504. https://doi.org/10.1093/treephys/27.10.1493

Huang ZS, Cheng Q (2016) Analysis of the optimal rotation of eucalypt carbon sequestration forests under various scenarios. Resour Environ Yangtze Basin 25(S1):25–31

Hurmekoski E, Myllyviita T, Seppälä J, Heinonen T, Kilpeläinen A, Pukkala T, Mattila T, Hetemäki L, Asikainen A, Peltola H (2020) Impact of structural changes in wood-using industries on net carbon emissions in Finland. J Ind Ecol 24(4):899–912. https://doi.org/10.1111/jiec.12981

Hurmekoski E, Kunttu J, Heinonen T, Pukkala T, Peltola H (2023) Does expanding wood use in construction and textile markets contribute to climate change mitigation? Renew Sustain Energy Rev 174:113152. https://doi.org/10.1016/j.rser.2023.113152

Jiang L, Zhang XQ, Duan AG, Zhang JG (2022) Annual tree diameter growth model of Chinese fir plantations including different

stand density indices. For Res 35(4):123–129. https://doi.org/10.13275/j.cnki.lykxyj.2022.004.013
Jin XJ, Pukkala T, Li FR, Dong LH (2017) Optimal management of Korean pine plantations in multifunctional forestry. J for Res 28(5):1027–1037. https://doi.org/10.1007/s11676-017-0397-4
Kaipainen T, Liski J, Pussinen A, Karjalainen T (2004) Managing carbon sinks by changing rotation length in European forests. Environ Sci Policy 7(3):205–219. https://doi.org/10.1016/j.envsci.2004.03.001
Liski J, Pussinen A, Pingoud K, Mäkipää R, Karjalainen T (2001) Which rotation length is favourable to carbon sequestration? Can J for Res 31(11):2004–2013. https://doi.org/10.1139/x01-140
Liski J, Palosuo T, Peltoniemi M, Sievänen R (2005) Carbon and decomposition model Yasso for forest soils. Ecol Model 189(1–2):168–182. https://doi.org/10.1016/j.ecolmodel.2005.03.005
Liski J, Lehtonen A, Palosuo T, Peltoniemi M, Eggers T, Muukkonen P, Mäkipää R (2006) Carbon accumulation in Finland's forests 1922–2004 -an estimate obtained by combination of forest inventory data with modeling of biomass, litter and soil. Ann for Sci 63(7):687–697. https://doi.org/10.1051/forest:2006049
Lu LL, Wang Z, Zhang XQ, Zhang JG (2021) Individual tree diameter growth model of Chinese fir plantations using Bayesian model averaging and stepwise regression approaches. Sci Silv Sin 57(9):87–97
Mäkinen H, Hynynen J, Siitonen J, Sievänen R (2006) Predicting the decomposition of scots pine, Norway spruce and birch stems in Finland. Ecol Appl 16(5):1865–1879. https://doi.org/10.1890/1051-0761(2006)016[1865:ptdosp]2.0.co;2
Nabuurs GJ, Schelhaas MJ (2002) Carbon profiles of typical forest types across Europe assessed with CO2FIX. Ecol Indic 1(3):213–223. https://doi.org/10.1016/s1470-160x(02)00007-9
Olson JS (1963) Energy storage and the balance of producers and decomposers in ecological systems. Ecology 44(2):322–331. https://doi.org/10.2307/1932179
Pasalodos-Tato M, Pukkala T, Alboreca AR (2010) Optimal management of *Pinus pinaster* in Galicia (Spain) under risk of fire. Int J Wildland Fire 19(7):937–948. https://doi.org/10.1071/wf08150
Peltoniemi M, Mäkipää R, Liski J, Tamminen P (2004) Changes in soil carbon with stand age -an evaluation of a modeling method with empirical data. Glob Change Biol 10(12):2078–2091. https://doi.org/10.1111/j.1365-2486.2004.00881.x
Peng W, Pukkala T, Jin XJ, Li FR (2018) Optimal management of larch (*Larix olgensis* A. Henry) plantations in Northeast China when timber production and carbon stock are considered. Ann for Sci 75:63. https://doi.org/10.1007/s13595-018-0739-1
Peng YX, Li FR, Liu F, Dong LH (2020) Prediction models of sapwood density, heartwood density, and bark density in *Larix olgensis* plantation. Chin J Appl Ecol 31(4):1113–1120. https://doi.org/10.13287/j.1001-9332.202004.007
Pukkala T (2006) Optimising the semi-continuous cover forestry of Finland. Allg Forst Jagdztg 177(8–9):141–149
Pukkala T (2011) Optimizing forest management in Finland with carbon subsidies and taxes. For Policy Econ 13(6):425–434. https://doi.org/10.1016/j.forpol.2011.06.004
Pukkala T (2014) Does biofuel harvesting and continuous cover management increase carbon sequestration? For Policy Econ 43:41–50. https://doi.org/10.1016/j.forpol.2014.03.004
Pukkala T (2018) Carbon forestry is surprising. For Ecosyst 5:11. https://doi.org/10.1186/s40663-018-0131-5
Pukkala T (2020a) At what carbon price forest cutting should stop. J for Res 31(3):713–727. https://doi.org/10.1007/s11676-020-01101-1
Pukkala T (2020b) Calculating the additional carbon sequestration of finnish forestry. J Sustain for 41(7):624–641. https://doi.org/10.1080/10549811.2020.1792935
Pukkala T, Lähde E, Laiho O (2011) Using optimization for fitting individual-tree growth models for uneven-aged stands. Eur J for Res 130(5):829–839. https://doi.org/10.1007/s10342-010-0475-z
Pukkala T, Lähde E, Laiho O (2014) Stand management optimization -the role of simplifications. Forest Ecosyst 1:3. https://doi.org/10.1186/2197-5620-1-3
Raymer AK, Gobakken T, Solberg B (2011) Optimal forest management with carbon benefits included. Silva Fenn 45(3):395–414. https://doi.org/10.14214/sf.109
Richards FJ (1959) A flexible growth function for empirical use. J Exp Bot 10(2):290–301. https://doi.org/10.1093/jxb/10.2.290
Rong JT, Lei XD, Zhang HR, Feng QX (2012) Forest management planning incorporating values of timber and carbon. J Northwest for Univ 27(02):155–162
Schelhaas MJ, van Esch PW, Groen TA, et al. (2004) CO2FIX V 3.1—a modelling framework for quantifying carbon sequestration in forest ecosystems. Alterra-rapport 1068
Shen HL, Ding BY, Shen GF, Chen AM (1996) Decomposing dynamics of several coniferous and broadleaved litters in Mongolian Scots pine plantation. Sci Silv Sin 32(05):393–402
Song L, Jin XJ, Pukkala T, Li FR (2023) Research on multi-objective management schedules of *Larix olgensis* plantations. J Nanjing for Univ Nat Sci Ed 47(02):150–158
Tikkanen OP, Heinonen T, Kouki J, Matero J (2007) Habitat suitability models of saproxylic red-listed boreal forest species in long-term matrix management: cost-effective measures for multi-species conservation. Biol Conserv 140:359–372. https://doi.org/10.1016/j.biocon.2007.08.020
Tong QP, Jin XJ, Pukkala T, Dong LH, Li FR (2024) Stochastic optimization of the management schedule of Korean pine plantations. Forests 15(6):935. https://doi.org/10.3390/f15060935
Tong QP, Jin XJ, Pukkala T, Dong LH, Li FR (2025) Adaptive optimisation of the management of Korean pine plantation. For Ecosyst 13:100326. https://doi.org/10.1016/j.fecs.2025.100326
Tuomi M, Laiho R, Repo A, Liski J (2011) Wood decomposition model for boreal forests. Ecol Model 222(3):709–718. https://doi.org/10.1016/j.ecolmodel.2010.10.025
Van Kooten GC, Binkley CS, Delcourt G (1995) Effect of carbon taxes and subsides on optimal forest rotation and supply of carbon services. Am J Agric Econ 77(2):365–374. https://doi.org/10.2307/1243546
Vanninen P, Mäkelä A (1999) Fine root biomass of Scots pine stands differing in age and soil fertility in southern Finland. Tree Physiol 19(12):823–830. https://doi.org/10.1093/treephys/19.12.823
Wen LN, Zhang HG, Sun T, Zhang ZJ, Zan P, Gu WP, Ma PY, Cao FY, Mao ZJ (2019) Fine root decomposition and N dynamics of *Larix gmelinii* at different soil depths. Acta Ecol Sin 39(13):4865–4871. https://doi.org/10.5846/stxb201806251392
Yang HQ, Ji CY, Yang H, Nie Y, Chen XL (2013) Global climate change and China's contribution to carbon reduction: based on carbon storage accounting of Chinese harvested wood products. J Nat Resour 28(12):2023–2033. https://doi.org/10.11849/zrzyxb.2013.12.001
Yatskov M, Harmon ME, Krankina ON (2003) A chronosequence of wood decomposition in the boreal forests. Can J for Res 33(7):1211–1226. https://doi.org/10.1139/x03-033
Zhang ZX (2008) Dendrology (Northern China Edition). China Forestry Publishing House, Beijing
Zhang DL, Mao ZJ, Zhu SY, Zhou B (2008) Litter falls of 6 major forest stands in Maoershan Mountain of Heilongjiang Province. Bull Bot Res 28(01):104–108
Zhang XQ, Zhang JG, Duan AG (2014) Tree-height growth model for Chinese fir plantation based on Bayesian method. Sci Silv Sin 50(3):69–75
Zhao LF, Li CM, Tang SZ (2013) Individual-tree diameter growth model for fir plantations based on multi-level linear mixed effects

models across southeast China. J for Res 18:305–315. https://doi.org/10.1007/s10310-012-0352-3

Zhu Y, Zhao R, Zhang HG, Gu WP, Long FQ, Mao ZJ, Sun T (2023) Coarse root decomposition and its control factors among 10 co-occuring common tree species in a temperate forest, Noreast China. Acta Ecol Sin 43(16):6682–6690

Zubizarreta-Gerendiain A, Pukkala T, Peltola H (2019) Effect of wind damage on the habitat suitability of saproxylic species in a boreal forest landscape. J for Res 30(3):879–889. https://doi.org/10.1007/s11676-018-0693-7

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