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Effect of initial pools on carbon balance calculations – a case of larch plantations in northeastern China

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Abstract. Carbon dioxide (CO_2) released during the decomposition of harvest residues reduces the net carbon sequestration of stands planted on clear-felled sites. All other dead organic materials (DOM) present in the stand, such as litter and dead trees, also decompose and release CO_2 into the atmosphere. Carbon is also released when discarded wood products made from previously harvested wood decay. Carbon sequestration is overestimated, especially in young stands, if the CO_2 released from DOM and discarded wood products is ignored in calculations. This study developed models to predict the biomass of DOM pools in the stand and the remaining biomass of products made from previously harvested wood. Initializing these biomass pools with the models and simulating DOM decomposition and product disposal helps eliminate overestimates in the carbon sink calculations for young plantations. When these models were integrated into simulation software, it showed that a young larch stand planted on a clear-felled site acts as a carbon source for about 10 years. Thinning treatments convert the stand into a carbon source for 3–7 years. Optimization with carbon subsidies and taxes indicated that higher CO_2 prices extend the optimal rotation length and increase the average carbon stock of the rotation. However, carbon pricing never turned the stand into a permanent carbon sink. Carbon sequestration in Chinese plantation forests can be improved by reducing thinning and increasing rotation lengths. The positive effects last as long as it takes to adopt the revised management practices across all forests.

1 Introduction

Forests have a dual role in climate change mitigation. On one hand, the photosynthesis of forests removes carbon dioxide (CO_2) from the atmosphere. On the other hand, forests and wood products store carbon. The CO_2 sequestrated in photosynthesis is stored in three carbon pools: live trees, dead organic materials (DOM), and wood products (referred to as harvested wood products, HWP). Given that climate warming depends on atmospheric CO_2 levels, it may be argued that the storage effect is more crucial for climate change mitigation than the carbon sequestration, as high carbon stocks in forests and wood products keep much carbon out of the atmosphere, slowing climate warming.

Carbon sequestration and carbon stocks are closely interconnected because carbon is sequestered permanently only if the sizes of the carbon stores in live trees, DOM, and HWP are permanently increased. Therefore, carbon forestry may aim either at

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maximizing carbon sequestration or carbon stocks. Previous studies (e.g. Heinonen et al., 2017) have shown that reduced harvest levels, i.e., enlarged carbon stocks, increased annual carbon sequestration in Finnish forests for at least 100 years, even when the substitution effects of wood products were considered. Substitution effects refer to reduced emissions from fossil fuels due to the use of wood products and biofuels. The increase in carbon sequestration was larger the more cuttings were reduced. Pukkala (2017) found that no-cutting management had a higher 100-year carbon sequestration than a scenario in which harvests were equal to volume increment. The substitution effects of wood products were considered in this study. Other studies show that maximizing carbon sequestration leads to low harvest levels and high carbon stocks (e.g., Pukkala, 2018).

The carbon sequestration of forests can be described by carbon balance, which is the net difference between carbon sequestration and carbon release during a given period. A positive balance means that carbon is sequestrated, i.e., the total carbon stock of live trees, DOM, and HWP increases. A related concept is the carbon sink, which measures the change in the amount of CO_2 in the atmosphere. Since carbon sequestration reduces atmospheric CO_2, a negative carbon sink corresponds to carbon removal and a positive carbon balance.

Some studies suggest that the carbon sequestration potential of the large tree plantations of northeastern China should be considered in forest management (Jin et al., 2017; Pukkala, 2018; Dong et al., 2020, 2022). Young plantations grow rapidly, and the fast-growing biomass quickly removes CO_2 from the atmosphere and converts it into tree biomass (Harmon et al., 1990; Rørstad, 2022; Stupak et al., 2025; Zheng et al., 2025). However, if the plantation is established on a clear-felled site, the harvest residues of the clear-felling, such as the roots, stumps, and branches of the cut trees, decompose, releasing CO_2 into the atmosphere.

A portion of the carbon in harvested trees is stored in short-lived wood products. The stored carbon is usually released back to the atmosphere at the end of the wood products' lifetime, either when discarded products are used as biofuel or when they decompose in landfills or elsewhere (Geng et al., 2017; Buendia et al., 2019). If the releases from harvest residues and discarded products are considered in carbon calculations, a young plantation may be a carbon source rather than a sink (Liski et al., 2001).

The above discussions indicate that ignoring the decomposition of initial DOM and HWP stocks gives a positively biased picture of the climate change mitigation effect of tree plantations established on clear-felled sites. Analyses over longer time horizons might even reveal that there are no mitigation effects at all, since the new plantation is only sequestrating CO_2 that was released earlier, because of clear-felling (Liski et al., 2001; Pukkala, 2011).

There are a few ways to accommodate the CO_2 release from DOM and HWP in carbon balance calculations. One way is to simulate the examined management schedule over several rotations so that the post-clear-felling DOM and HWP pools are used as the initial pools of a new rotation (Pukkala, 2011). The carbon balance of the rotation is calculated from the last simulated rotation. Another possibility is to initialize the DOM and HWP pools with models (Pukkala, 2014). This approach is more convenient for forest management planning, where the initial stands can be of any age, and the simulations often cover a fixed period (e.g., 10 or 20 years). The past development and management of the stands are seldom known, which makes it difficult to simulate the same management schedule over several rotations.

Carbon sequestration subsidies can be used as a policy instrument to increase carbon sequestration in privately owned forests. Increases in carbon stocks can be subsidized, and decreases in carbon stocks can be penalized or taxed (Pohjola and Valsta, 2007). Previous studies show that optimal rotation lengths and biomass stocks increase with this type of carbon payments (Diaz-Balteiro and Rodriguez, 2006; Raymer et al., 2011; Quintero-Méndez and Jerez-Rico, 2019; Dong et al., 2022; Rørstad, 2022). Usually, as the carbon price increases, timber production and the discounted net incomes from timber production decrease, while carbon sequestration and the total NPV increase significantly (Kucuker, 2019).

There is already research on the management optimization of Chinese tree plantations that considers carbon balance or carbon stocks, in addition to wood production and economic timber benefits (Deng et al., 2022; Dong et al., 2022; Liu et al., 2023; Zhang et al., 2023; Lin et al., 2024; Jiang et al., 2026). However, the Chinese studies have assumed that the initial carbon stock is zero. Raymer et al. (2009) focus on CO_2 flows and treat the initial carbon stocks from the previous rotation as sunk costs. Holtsmark et al. (2013) remark that initial stocks of DOM and wood products do not affect optimal harvest age, which means that they can be ignored if the only target of the analysis is to find the optimal harvest ages.

However, even if the initial stocks do not affect optimal management, they affect carbon balance estimates, which are positively biased if the initial stocks are ignored (Pukkala, 2014). These biases may lead to erroneous carbon accounting. They may also lead to excessive carbon subsidies, especially in young, fast-growing forests planted on clear-felled sites.

Carbon calculations that consider only living tree biomass tend to overestimate the carbon sequestration of young forests because the decomposition of the harvest residues of a recent clear-felling is ignored. Several products prepared from the clear-felled trees, especially biofuel and pulp-and-paper products, also have short lifespans, which means that most of their carbon returns to the atmosphere during the first years of a newly planted forest.

The objective of this study was to develop a method for calculating the carbon balance of a planted forest in an individual-tree simulation, including initial carbon stocks of DOM and wood products. 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 carbon balance of larch plantations. The model enables managers and policymakers to analyze the effects of carbon pricing on optimal stand management and estimate the carbon balances of alternative management systems.

Specifically, the study developed models for initializing the DOM and HWP pools of larch stands planted on clear-felled sites. These models were integrated into a simulation–optimization software, which allows the maximization of the discounted net incomes, with or without carbon pricing. The software was subsequently used to compare carbon balance estimates obtained with and without the initialization of the DOM and product pools. The difference is an estimate of the error caused by omitting the initial pools. The enhanced simulation-optimization system was also used to optimize plantation management under different carbon prices. These analyses indicate how carbon subsidies or taxes would affect optimal forest management and how much they would increase carbon sequestration.

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2 Materials and methods

2.1 Modelling the initial DOM and HWP pools

The recent method of Jiang et al. (2026) was used to produce simulated data for modelling the sizes of the DOM and HWP pools. The method simulates the dynamics of three biomass pools: (1) live trees, (2) DOM, and (3) HWP. The DOM pool includes dead trees, harvest residues, and litter. The decomposition of dead trees and harvest residues is simulated at the tree level, using annual decomposition rates specified separately for stems, roots, branches, and foliage.

The carbon dynamics of live trees and HWP are simulated at the tree level. The carbon dynamics of DOM are simulated at the tree level for dead and harvested trees. When a tree dies, the decomposition of its stem, branches, foliage, and roots is simulated, using different decomposition rates for each biomass component. A harvested tree is partitioned into different harvest residue components (branches, foliage, and roots) and wood products categories (sawn wood, particle boards, pulp and paper, biofuels). The decomposition of each residue and wood product category is simulated separately. The carbon dynamics of litter are based on annual turnover rates and the annual decay rates of different litter types (leaf, branch, and root litter).

The decomposition of DOM and the disposal of HWP are simulated using the following model (Olson, 1963):

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

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.

In the simulation, the stems of harvested trees were first divided into timber assortments, and each assortment was further divided into end products (Table 1). The volumes of timber assortments were calculated with a taper model (Peng et al., 2018). The treetop and the branches, foliage, and roots of harvested trees were moved from the live biomass pool to the DOM pool. Carbon releases from discarded products were calculated from annual product disposal rates, which were derived from the half-lives of different product types (Buendia et al., 2019). The product half-lives were 35 years for sawn wood, 20 years for particle board, 3 years for pulp and paper, and 2 years for biofuel, leading to annual disposal rates (k in Eq. (1)) of 0.0198 for sawn wood, 0.0346 for particle board, 0.231 for pulp and paper, and 0.347 for biofuel.

The method of Jiang et al. (2026) does not initialize the DOM and HWP pools; it predicts the carbon dynamics of DOM and HWP inputs that appear during the simulation. Therefore, simulated data for modelling the DOM and HWP pools were produced iteratively, as was done earlier in Finland (Pukkala, 2020b).

Five sample plots representing different site fertility categories were used to produce simulated data for modelling. The site indices of the plots ranged from 18.1 to 25.6 m (dominant height at 40 years), and the stand age ranged from 12 to 27 years. Alternative management schedules were simulated for each plot by varying the rotation length, thinning years, and thinning intensity. The annual DOM and HWP pools of the simulated schedules, together with growing stock variables, were used to fit preliminary models that show the sizes of the DOM and HWP pools as a function of stand age, site index, and basal area.

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It was assumed that the DOM and HWP pools immediately after clear-felling were the initial pools of a new plantation (at age 0).

Table 1: Minimum dimensions, stumpage prices, and the proportions of wood products for different timber assortments.

Assortment	Minimum top diameter, cm	Minimum log length, cm	Stumpage price, RMB·m^3	Proportions of product types			
				Sawn wood	Particle board	Pulp and paper	Biofuel
Large sawlog	24	4	850	0.4	0.3	0.1	0.2
Medium-sized sawlog	18	4	650	0.4	0.3	0.1	0.2
Small sawlog	12	4	400	0.4	0.3	0.1	0.2
Pulpwood log	6	2	250	0	0	0.5	0.5
Fuelwood log	3	1	80	0	0	0	1.0

Then, the simulation of alternative management schedules was repeated so that the DOM and HWP pools were initialized with the preliminary models. These simulations produced data for new versions of the initialization model used in the next simulation round. This process was repeated five more times, which was found sufficient for the models and the temporal development of the DOM and HWP pools to stabilize.

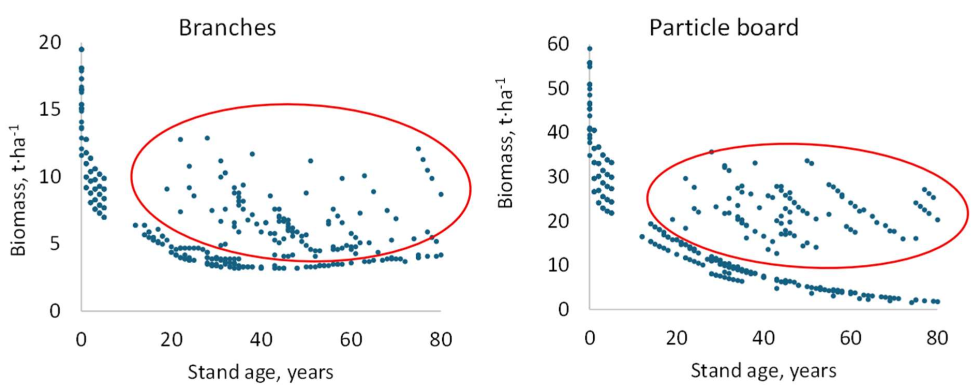

Figure 1: Examples of simulated data for modelling the sizes of the DOM and HWP pools.

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Figure 1 shows examples of the simulated DOM and WP data. Young plantations were associated with large pools due to the recent clear-felling of the previous tree generation. The pool sizes decreased quickly due to product disposal and decomposition of harvest residues. However, the pool sizes increased again after thinning treatments, which produced harvest residues and new products. The thinning-induced increments in the sizes of the DOM and HWP pools are shown within red ellipses in Fig. 1.

When the sizes of the DOM and HWP pools of a certain stand are predicted, there may be no information available on the year and intensity of past thinning. However, a low basal area is a sign of recent thinning and can therefore be used as a surrogate to predict the effect of thinning on the sizes of the DOM and HWP pools. Based on this rationale, preliminary analyses of the simulated data and previous research (Pukkala, 2020b), the following model form was used for both DOM and HWP:

$$BM = exp(a0 + a1ln(T + 0.1) + a2T + a3SI + a4ln(T + 1) \times G)\ , \quad (2)$$

where *BM* is the biomass of the DOM or HWP pool ($t\cdot ha^{-1}$), *T* is stand age (years since planting), *SI* is site index (m), and *G* is the stand basal area ($m^2 ha^{-1}$). The model was fitted separately for the following DOM components: stems, branches, foliage, roots, and fine roots. The HWP components were sawn wood, particle board, pulp and paper, and biofuel. These are the same components as used in Jiang et al. (2026). The hypothesis was that the pool sizes decrease with stand age, at least in young plantations. The DOM pools may increase again in older stands due to increased mortality and litter production. Improving site index should increase the pool sizes, as fertile sites produce more timber, litter, and harvest residues. A low basal area is associated with a recent thinning treatment and should therefore increase the sizes of the HWP pools and also some DOM pools. Especially, the DOM pools of branches and roots should increase in thinning because they are the main components of harvest residues.

2.2 *Optimization*

The initialization models for the DOM and HWP pools were used in management optimization, where the objectives were discounted net incomes (NPV) from timber sales, subsidies from carbon sequestration, and taxes from carbon releases. All costs and incomes were discounted to the starting year of the simulation.

Since NPV needs to be calculated to infinity, we simulated one full rotation and assumed that the same rotation is repeated to infinity. Obtaining results for full rotation required that the development of the new plantation and its carbon pools be simulated until the age of the new plantation was equal to the age of the initial stand. The NPV was calculated as (Faustmann, 1849):

$$NPV = NPV_{Rotation}\left[1 - \frac{1}{(1+0.01\ \ )^{T}}\right]^{-1}\ , \quad (3)$$

where NPV_{Rotation} is the net present value of the simulated rotation, *T* is the rotation length and *r* is the discount rate in percent. NPV_{Rotation} was calculated as

$$NPV_{Rotation} = \sum_{i=0}^{T} \frac{Cost_i + Income_i + Subsidy_i + Tax_i}{(1+0.01\ \ )^{i}}\ , \quad (4)$$

where $Cost_i$, $Income_i$, $Subsidy_i$, and Tax_i are, respectively, the management cost, income from timber sales, subsidy from carbon sequestration, and tax from carbon releases *i* years since the start of the simulation.

Stand development and cuttings were simulated on an individual-tree basis from the age of the initial stand to clear-felling (Jiang et al., 2026). This simulation yielded the income from timber sales and the annual changes in carbon stocks. It was assumed that an increase in carbon stock was subsidized and a decrease was taxed. The costs from the establishment of a new tree plantation were discounted from the clear-felling year, and the tending costs of young plantations were discounted from the tending year. The stand establishment cost (site preparation and planting) was 5500 RMB·ha^{-1} in the clear-felling year, and the tending cost was 500 RMB·ha^{-1} ten years later (Jiang et al., 2026).

To calculate carbon sinks and releases at the beginning of the new rotation (before the age of the initial stand), the development of the biomass pools of live trees, DOM and HWP was simulated in a simplified way. Simplification was required because there are no models in Heilongjiang for simulating the development of very young larch plantations on an individual-tree basis. The development of the HWP pools after clear-felling was obtained by simulating the decomposition of the post-clear-felling pools of sawn wood, particle board, pulp and paper, and biofuel, using Eq. (1) and annual disposal rates of 0.0198, 0.0346, 0.231, and 0.347 for sawn wood, particle board, pulp and paper, and biofuel, respectively.

The same method could not be used for DOM because the new plantation produces new litter to the DOM pool. The size of the DOM pool depends on the decomposition of the initial, post-clear-felling pool, litter production of the new plantation, and decomposition of this litter. Therefore, the initialization models developed for the DOM pools were used to calculate the sizes of the DOM pools at different ages of the new plantations.

To estimate the carbon pool of live trees, the total biomass was calculated for several young plots, using the biomass models of Dong et al. (2016) for branches, foliage, and roots. The stem biomass was calculated by multiplying the stem volume by wood density. Then, the development of the stands without any thinning was simulated for a few years (Fig. 2). The initial and simulated live tree biomasses of these plots were used as data to fit the following model for the biomass accumulation in young plantations (see Fig. 2):

$$BMLive = exp(-2.905456 + 1.764569 ln\,(T + 0.1) - 0.021231T + 0.124269SI)\,, \tag{5}$$

where BM_{Live} is the total biomass of living trees (t·ha^{-1}), T is stand age (years since planting) and SI is site index (m).

The management was optimized for two plots, one representing site index 18 m and the other representing site index 22 m. Optimization was repeated with the following CO_2 prices: 0, 200, 400, and 600 RMB·t^{-1}.

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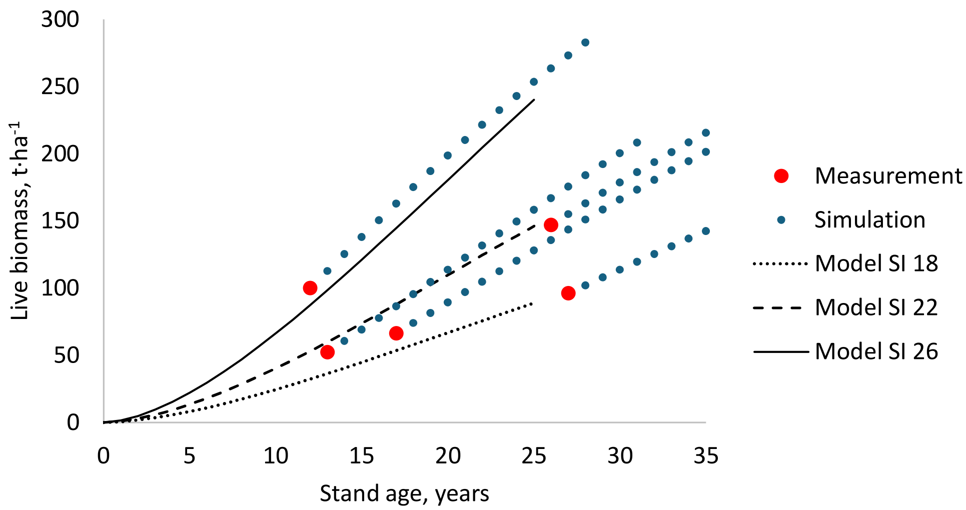

Figure 2: Measured and simulated biomass for five larch plots (dots) and predicted biomass development (lines) for three site indices (Model 18, 22 and 26 m).

3 Results

3.1 *Models for initial biomass stocks*

The models for predicting the sizes of DOM pools (Eq. (2), Table 2) showed that the pool sizes were large in young plantations, due to recent clear-felling, but the pool sizes decreased rapidly due to the decomposition of harvest residues and the small litter production of young plantations. Improving site index increased the pool size because of higher amounts of harvest residues and litter. The effect of age was modified by the stand basal area in such a way that the pool sizes were larger when the basal area was low. This effect is explained by the fact that a low basal area is associated with thinning, and thinning treatments produce harvest residues to the DOM pools. The effect of basal area was strongest on the DOM pools of branches and roots, because they are the largest components of harvest residues.

The relationships between stand attributes and the sizes of initial HWP pools were like those for the DOM pools (Table 3, Fig. 3). Logically, the HWP pools were largest in a young plantation. i.e., soon after clear-felling. A decrease in basal area increased the sizes of all HWP pools, the more the older the stand. The reason was that a low basal area at older stand age is a consequence of a recent thinning, which increases the size of the product pools.

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Table 2: Parameters of the initialization models (Eq. (2)) of the DOM pools. *T* = stand age (years), *SI* = site index (m), G = stand basal area (m^2ha^{-1}).

Predictor	Stems	Branches	Foliage	Roots	Fine roots
Intercept	1.9357	1.4538	2.0058	2.9962	1.2731
ln(*T*+0.1)	-0.1696	-0.1979	-0.0487	-0.2409	-0.1095
T	0.0120	0.0154	-0.0071	0.0217	-0.0075
SI	0.0662	0.0424	0.0206	0.0189	0.0185
ln(*T*+1)*G*	0.0031	-0.0066	0.0059	-0.0077	0.0052
RMSE	5.12	1.63	1.55	6.05	0.69
RMSE %	14.9	21.3	12.6	27.7	14.7

Table 3: Parameters of the initialization models (Eq. (2)) of the HWP pools. *T* = stand age (years), *SI* = site index (m), G = stand basal area (m^2ha^{-1}).

Predictor	Sawn wood	Particle board	Pulp and paper	Biofuel
Intercept	2.0952	2.1649	0.9922	1.8180
ln(*T*+0.1)	-0.1807	-0.1716	-0.2935	-0.3504
T	0.0236	0.0220	0.0274	0.0305
SI	0.0769	0.0615	0.0665	0.0419
ln(*T*+1)*G*	-0.0104	-0.0127	-0.0203	-0.0208
RMSE	8.04	5.04	2.30	3.53
RMSE %	25.3	23.1	38.0	43.4

Figure 3 visualizes the initialization models for a site index of 22 m in an unthinned young stand. All DOM pools decrease at first, but the decrease in the foliage pool is small, and it begins to increase again at 10 years. This is because foliage decomposes fast and is closely correlated with the annual litter production of the growing stock. The DOM pool of stems also begins to increase soon, at 10 years, because, in managed forests, there is not much dead stem wood at clear-felling, and the self-thinning of a dense non-thinned plantation begins at a young age. In Heilongjiang, planting densities are high, typically 4400 trees per hectare, and therefore, self-thinning commences early.

Logically, the sizes of the HWP pools of a young pre-commercial stand decreased with age, as there was no new input before the first thinning treatment (Fig. 3b). The largest product pools were sawn wood and particle board, due to the durability of these products.

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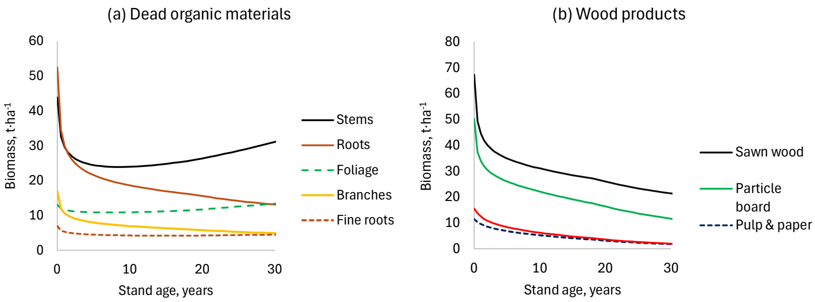
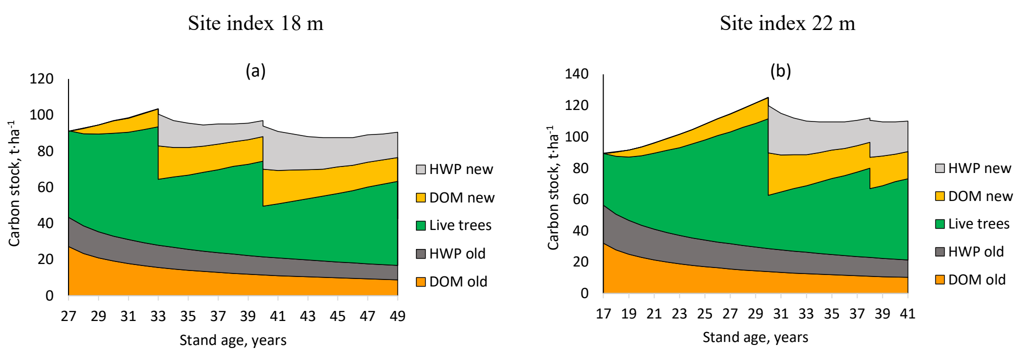


Figure 3: Predicted size of the biomass pools of dead organic materials (a) and wood products (b) for a site index of 22 m in an unthinned stand.

3.2 *Effect of initialization on CO_2 balance estimates*

The effects of pool initialization on carbon balance estimates are visualized in Fig. 4. The results are for an optimization where NPV was maximized without carbon subsidies and taxes. Before the first thinning, the pre-commercial stand sequestrated carbon in living biomass and dead organic material at a rate of approximately 17 (SI 18 m) or 18 (SI 22 m) tons of CO_2 per hectare and year (Fig. 4c and d). However, if the decomposition of the initial DOM and HWP pools was considered ('DOM old' and 'HWP old' in Fig. 4), the average annual CO_2 sink of the pre-commercial stand was only 7 (SI 18 m) or 10 (SI 22 m) tons of CO_2 per hectare and year. Decomposition of the initial DOM and HWP pools continued to decrease the carbon balance estimate over the whole rotation.



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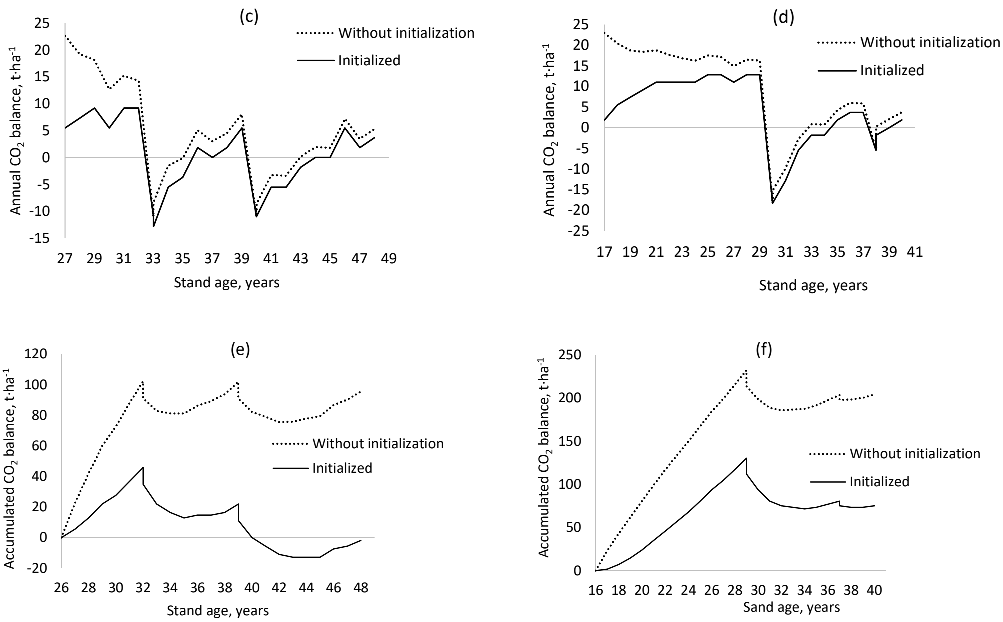

Figure 4: Development of the carbon pools when NPV is maximized with a 4% discount rate with a zero carbon price (a, b), the annual carbon balance estimate calculated with (solid line) or without (dotted line) the initialization of the DOM and HWP pools (c, d), and the accumulated CO_2 sequestration calculated with and without pool initialization (e, f). The carbon balance is expressed as tons of CO_2 per hectare (one ton of C corresponds to 3.67 tons of CO_2). The carbon balances (c, d) are for the next year, and the accumulated balances are totals by the end of a certain year (since the beginning of the simulation).

Both stands were carbon sources for 3–4 years after thinning, except for the second very mild thinning in site index 22 m (Fig. 4c and d). When the initial DOM and HWP pools were ignored, the calculation suggested that the stand removed approximately 100 (SI 18 m) or 200 (SI 22 m) tons of CO_2 from the atmosphere (Fig. 4e and f, dotted lines). This sequestration happened before the first commercial thinning. Later, both decreases and increases in the amount of sequestrated CO_2 were observed.

The picture was very different when the decomposition of the initial DOM and HWP pools was included in the calculation (Fig. 4e and f, continuous lines). The stand representing SI 18 m removed only 40 tons of CO_2 per hectare by the first thinning. Later, more CO_2 was released than sequestrated. The whole CO_2 budget of the simulated period (from 27 to 49 years) was zero, i.e., no CO_2 was removed from the atmosphere. On the better site (SI 22 m), the estimated amount of CO_2 sequestrated before the first thinning decreased from 232 to 130 tons of CO_2 per hectare. The estimate for the whole simulation period (17–41 years) decreased from 204 to 75 tons of CO_2 per hectare when the pools were initialized.

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3.3 *Effect of CO_2 price on optimal management*

An increase in the carbon price increased the optimal rotation length and decreased wood production (Table 4). The mean annual CO_2 balance increased from 0.45 t·ha^{-1} to 0.93 t·ha^{-1} in SI 18 m when the CO_2 price increased from 0 to 600 RMB·t^{-1}. On the other hand, there was no systematic increase in mean annual CO_2 sequestration on site index 22 m.

When the CO_2 price was 600 RMB·t^{-1}, carbon subsidies and taxes accounted for 80.8% (SI 18 m) or 87.2% of the total NPV, although the mean annual CO_2 sequestration of full rotation was not high (Table 4, Figs. 5d and 6d). The high share is explained by discounting and temporal differences between CO_2 subsidies and incomes from timber sales. Most of the CO_2 was sequestrated during the first years, whereas most income from timber sales was obtained much later, in the clear-felling year.

Table 4: Effect of CO_2 price on rotation length, wood production, and carbon sequestration when the net present value (NPV) is maximized.

	CO_2 price, RMB·t^{-1}			
	0	200	400	600
		Site index 18 m		
Rotation length, years	49	61	78	88
Wood production, m^{3}ha^{-1}a^{-1}	12.5	10.6	8.9	7.5
Mean CO_2 balance, t·ha^{-1}a^{-1}	0.45	0.70	0.80	0.93
Proportion of CO_2 of NPV, %	0	10.4	44.2	80.8
		Site index 22 m		
Rotation length, years	41	57	79	86
Wood production, m^{3}ha^{-1}a^{-1}	13.3	11.2	9.5	8.1
Mean CO_2 balance, t·ha^{-1}a^{-1}	1.84	1.86	1.43	1.96
Proportion of CO_2 of NPV, %	0	19.2	43.8	87.2

Figures 5 and 6 show that the total carbon sequestration of a full rotation was low in all cases; the total carbon stock (live trees + DOM + HWP) at the end of the simulation was only slightly larger than the initial carbon stock. This means that the optimal management removed little CO_2 from the atmosphere even when the CO_2 price was high.

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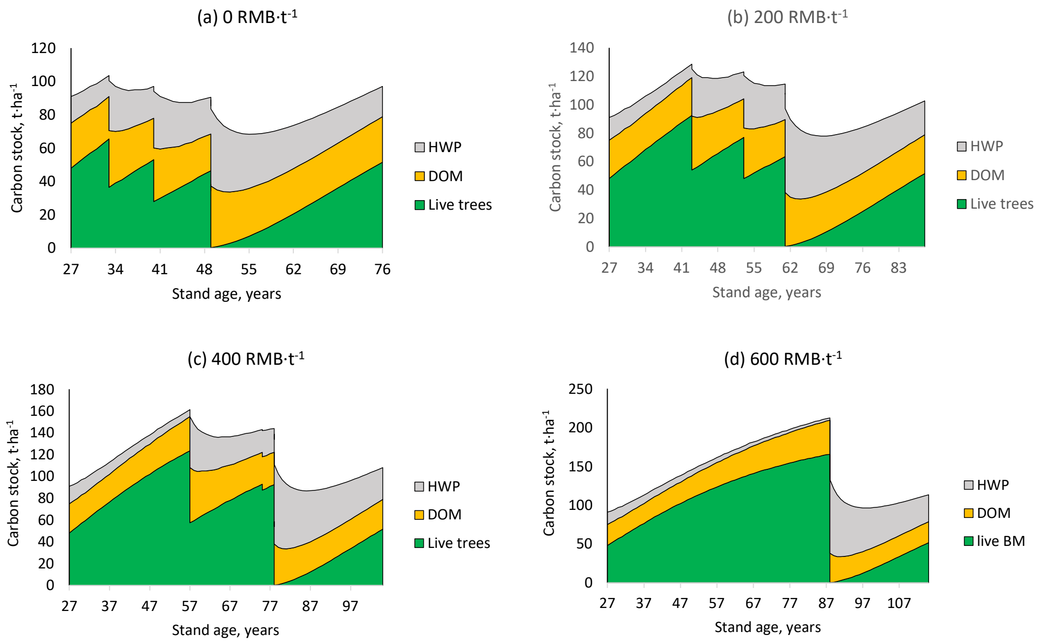
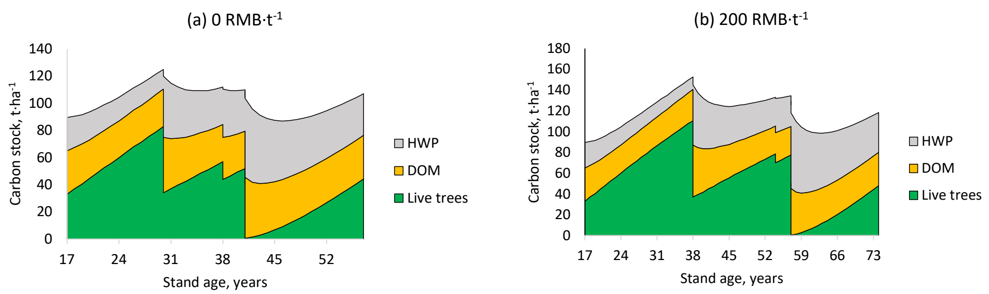


Figure 5: Development of carbon stocks in optimal cutting schedules for site index 18 m when NPV is maximized with CO_2 prices of 0, 200, 400, and 600 RMB·t^{-1}. The cutting schedule includes two thinnings and a clear-felling. The development of carbon stocks after clear-felling is simulated until the age of the initial stand. The DOM and WP pools are initialized with models developed in this study.



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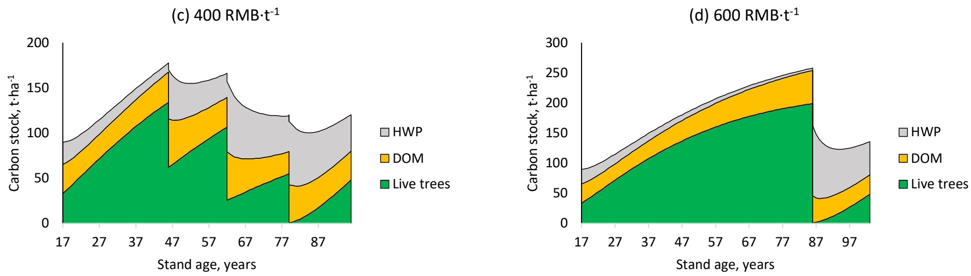

Figure 6: Development of carbon stocks in optimal cutting schedules for site index 22 m when NPV is maximized with CO_2 prices of 0, 200, 400, and 600 RMB·t^{-1}. The cutting schedule includes two thinnings and a clear-felling. The development of carbon stocks after clear-felling is simulated until the age of the initial stand. The DOM and WP pools are initialized with models developed in this study.

After clear-felling, the total carbon stocks of live trees, DOM, and HWP decreased for 5–10 years, meaning that young plantations were carbon sources for 5–10 years. When NPV was maximized without carbon payments, the carbon released after clear-felling was sequestered back during 24 years in SI 18 m and during 17 years in SI 22 m. The payback time increased with increasing carbon price because the carbon released due to clear-felling increased with the CO_2 price. Figs. 5 and 6 show that the older the clear-felled stand, the longer it takes to sequestrate back the released carbon.

Figs. 5 and 6 suggest that, in the long run, forest management does not permanently remove notable amounts of CO_2 from the atmosphere since the total carbon stock of live trees, DOM, and HWP does not increase during the time periods that correspond to one full rotation length. The conclusion is the same when the additional CO_2 sequestration, compared to a zero CO_2 price, is considered (Fig. 7). Carbon payments result in substantial additional carbon sequestration at first, but the additional sequestration turns into additional carbon release when the forest is clear-felled, leading to the outcome that the accumulated additional carbon sequestration obtained by carbon payments is close to zero during a time period that corresponds to the rotation length.

However, the picture was different when the average carbon stock of the stand during the rotation was considered (Fig. 8). The average carbon storage increased when management was optimized with increasing carbon prices. The difference in carbon stocks between CO_2 prices 0 and 600 RMB·t^{-1} was 67% in site index 18 m, and 71% in SI 22 m. The result means that shifting from management that is optimal without carbon payments to optimal management with a CO_2 price of 600 RMB·t^{-1} leads to a large carbon sequestration. However, this sequestration lasts only as long as the shift in forest management takes. Carbon sequestration due to a change in the management system is over when all stands are managed according to the new system for a full rotation. After that, the forest no longer generates permanent carbon benefits.

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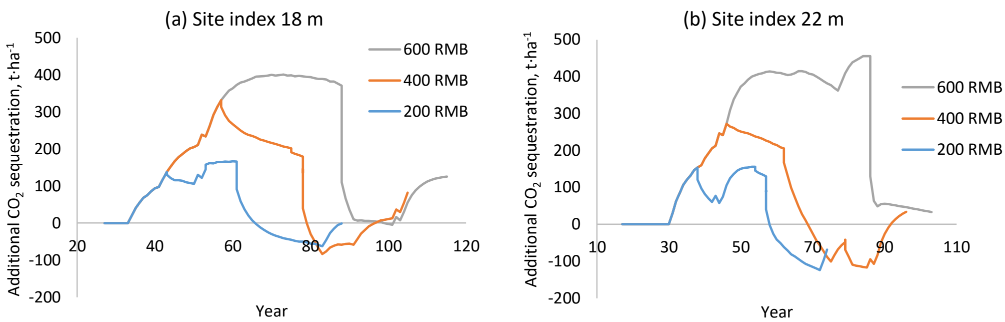

Figure 7: Accumulated additional CO_2 sequestration with CO_2 prices of 200, 400, and 600 RMB·t⁻¹, compared with optimal management with a zero CO_2 price.

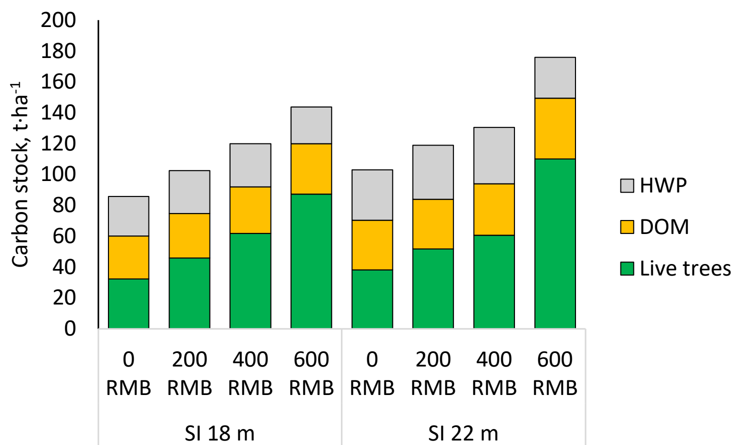

Figure 8: Average carbon stocks during the rotation when NPV is maximized with CO_2 prices of 0, 200, 400, and 600 RMB·t⁻¹.

If the management of larch plantations is changed from the schedule that is economically optimal for timber production (CO_2 price zero) to more carbon-oriented schedules (obtained with CO_2 prices of 200–600 RMB·t⁻¹), the additional carbon sequestration would be 1.0–2.2 tons of CO_2 per hectare and year in SI 18 m and 2.0–5.0 tons of CO_2 per hectare and year in SI 22 m, if the change in management is accomplished during a period equal to one rotation length of the carbon-oriented

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management, i.e., 57 to 88 years (Table 4). Therefore, changing forest management toward carbon-friendly systems would generate carbon benefits for several decades.

4 Discussion

4.1 *Contributions*

The main new contributions of the study were the initialization models for the DOM and HWP pools. They help remove biases in carbon calculations caused by omitting CO_2 releases from harvest residues and discarded wood products. The models were formulated in such a way that their use does not require information on past management. For example, the removals of past cuttings and years since thinning were not used as predictors since they are not always known. Therefore, the models can be easily used in forest planning and with typical forest inventory data.

This simplification decreased the accuracy of the models compared to a case where the management history of the stand is known precisely. The developed models predict the sizes of the DOM and HWP for managed stands and typical rotation ages. Postponed clear-felling would result in larger post-cutting pools, which in turn would increase the size of the post-cutting DOM and HWP pools and CO_2 releases of the new plantation, lengthening the payback time.

The lack of the effect of past removals is not a serious limitation of the models since practically all larch plantations are managed using regular thinning schedules and rotation lengths. However, one possibility to improve the models is to use the removals and years of past cuttings as additional predictors of the initialization models. These models could be developed as an alternative for cases where detailed information on management history is available.

Optimizations showed that an increase in carbon price increases the rotation length, even though it would decrease wood production. The same result has been obtained earlier in several studies (e.g., Liski et al., 2001, Pohjola and Valsta, 2007). Another result was that a no-thinning schedule was optimal with a high carbon price. This corresponds to the results of Pukkala (2020a), who found that it is economically optimal to stop all cuttings when the carbon price is high. The outcome of the calculations depends on the durability of dead-tree carbon stores compared to wood products. In some cases, the stems of dead trees can be more durable carbon stores than the products prepared from the stems of harvested trees (Pukkala, 2018). In these situations, it may be optimal to stop all harvesting, especially if the substitution effects of wood products are not considered or are low.

Another result of our study was that the mean annual carbon sequestration of a full rotation was near zero, even with a high carbon price. This leads to the conclusion that managed forests are never permanent carbon sinks. They are carbon sinks only as long as the sizes of the carbon stock grow, which cannot continue forever. When forests are managed in a certain way for long times, the sizes of the DOM and HWP pools will stabilize since carbon outputs due to DOM decomposition and product disposal will eventually reach the carbon inputs. The carbon pool of live biomass cannot grow infinitely either. Therefore, if substitution effects are ignored, forests are always only temporary carbon sinks. Fortunately, the sink effect can last decades or even centuries if rotation lengths are increased, thinnings are reduced, more forest is planted, and more durable products are prepared. This study showed that changing the management system towards carbon-smart forestry may increase the annual CO_2 sequestration of the larch plantations in northeastern China by 1–5 tons per hectare for about 60 to 90 years.

The conclusion that increasing importance of carbon sequestration in forest management leads to longer rotations and fewer thinnings in the larch plantations of northeastern China was drawn earlier by Jiang et al. (2026). Whereas we used carbon payments and NPV calculations as a means to analyze the effect of increasing importance of carbon sequestration, Jiang et al. (2026) maximized the average carbon stock of the rotation in multi-objective optimization. Assuming that a one-cubic-meter increase in stem volume corresponds to a CO_2 sequestration of one ton, a CO_2 price of 600 RMB·t^{-1} would correspond to a situation where the values on one cubic meter would be nearly the same as sold timber or increased carbon stock. This CO_2 price led to a 39–45-year increment in optimal rotation lengths. The increment in rotation length in Jiang et al. (2026) was 18–46 years when wood production and the average carbon stocks of the rotation were maximized with equal weights.

One reason for the differences between our results and earlier ones is discounting, which decreases the significance of CO_2 releases that occur in the distant future. The NPV from CO_2 payments would be positive if CO_2 is sequestrated first and the same amount of CO_2 is released later. Especially with high discount rates, releases far in the future have only a minor effect on the discounted value of carbon subsidies and taxes. Because the NPV of carbon payments can be positive without any long-term carbon removal, the use of discounted carbon payments in management optimization may be questionable. It is justified when it is important to sequester carbon soon, for instance, to gain time for the development of other technologies for removing CO_2 from the atmosphere.

Our calculations assumed that any carbon sequestration is subsidized to the landowner. Another approach is to subsidize only that carbon sequestration that is additional to the "business as usual" management, which may be the current management or a management that is economically optimal without carbon payments (Fig. 7). Paying only for additional management would not change the optimization results, but it would greatly reduce the society's cost of subsidizing carbon-oriented forest management.

Conclusions about the effect of carbon price on optimal management would be the same without the initialization of the DOM and HWP pools (Holtsmark et al., 2013) because the overestimate in carbon sequestration is the same for all management schedules that are evaluated in optimization. This conclusion is valid when the management of a stand does not affect the decomposition rates of the initial DOM and HWP pools.

The simulations of our study showed that a larch plantation is a carbon source for 3–4 years after a thinning treatment and 5–6 years after clear-felling. In Pukkala's earlier study (Pukkala, 2011), pine and spruce planted on clear-felled sites were carbon sources for about 10 years. These results do not mean that the negative effect of cutting is over when the stand is again a carbon sink. All cuttings lead to a "carbon debt" because carbon is released from the forest to the atmosphere (Rummukainen, 2026). In the case of larch plantations, the payback time of this debt was more than 10 years for the thinning treatment. In clear-felling, the payback time was found to be 24 years in SI 18 m and 17 years in SI 22 m in an economically optimal timber-oriented management (no carbon payments). However, the payback times were much longer in carbon-oriented management, where

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longer rotations were used, and the carbon stocks of the clear-felled stands were larger. Therefore, it is questionable to claim that young fast-growing plantation forests generate climate benefits, because they only sequester CO_2 that was released earlier. Long-lasting carbon benefits may be obtained if forest management is altered to a carbon-smart direction. The change in forest management should increase the average carbon stock of the forest. When this increase is over, the forest no longer permanently removes CO_2 from the atmosphere. However, the climate change mitigation effect of the forest continues, as high carbon stores of forests mean less CO_2 in the atmosphere. The more carbon there is in forests and wood products, the less there is CO_2 in the atmosphere.

Wood products may have substitution effects, i.e., the use of wood products and biofuels may decrease carbon emissions from fossil fuels and fossil-energy-intensive materials (Hurmekoski et al., 2023). Although substitution effects are not included in international carbon accounting, they affect the climate benefits of forest management. The substitution effects depend on what type of energy is used as an alternative to biofuels, and what energy sources are used to produce materials that are alternatives to wood products.

In China, coal is still used as energy (CET Programme, 2025), and replacing coal with biofuel therefore generates positive substitution effects. Fossil energy is also used in the steel and cement industries (China Iron and Steel Association, 2020; RMI & China Cement Association, 2022). However, when the energy sector is progressively decarbonized, the substitution effects of wood products and biofuels will gradually disappear. For example, Hurmekoski et al. (2023) calculated that the substitution effect of Finnish conifer sawn wood was 0.96 $tC \cdot tC^{-1}$ in 2020, but it will be only 0.35 $tC \cdot tC^{-1}$ in 2050. For fuelwood, the substitution effect was 0.57 $tC \cdot tC^{-1}$ in 2020 and 0.11 $tC \cdot tC^{-1}$ in 2050. Pulp and paper products have very low substitution effects. Therefore, substitution effects may not convert managed forests into permanent carbon sinks. Seppälä et al. (2019) calculated that the substitution effects of Finnish wood products and biofuels should be two to three times higher than they are now to warrant increased harvesting.

Appendix A

The dataset used in this study comprises field-measured forest inventory data obtained from larch plantation sample plots in Northeast China. The study area covers Heilongjiang Province (121°11′–135°05′ E, 43°26′–53°33′ N). These field-surveyed plots representing diverse site conditions provide the initial stand-level inputs for forest management simulations. The stand ages of selected plantations range from 12 to 27 years, with site indices varying between 18 m and 24 m, which were adopted as starting parameters for simulation scenarios. Summary descriptive statistics for these initial stands are summarised in Table A1, and diameter-class distributions of the surveyed sample plots are illustrated in Fig. A1.

Table A1: Basic information of Larch plantation sample plots

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Stand age, a	Site index, m	Stand density, trees·ha^{-1}	Mean DBH, cm	Stand dominant height, m	Stand basal area, m^2·ha^{-1}
27	18	1230	13.4	16.9	17
17	22	1283	11.2	14.0	13
13	24	1933	8.4	11.3	11

Figure A1: Stand diameter-class distributions under different stand ages and site indices.

Code and data availability

The authors do not have permission to share data.

Author contributions

Bo Jiang: Formal analysis, Writing - original draft, Visualization. Xingji Jin: Conceptualization, Formal analysis, Writing - review & editing, Data curation, Supervision, Project administration. Timo Pukkala: Conceptualization, Methodology, Software, Formal analysis, Supervision, Writing - review & editing. Fengri Li: Data curation, Writing - review & editing.

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Competing interests

The authors declare that there are no relevant financial or non-financial competing interests that could have influenced the work reported in this paper.

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