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Research paper

Carbon balance and economic performance of pine plantations for bioenergy production in the Southeastern United States

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ABSTRACT

Management strategies for loblolly pine (*Pinus taeda*) plantations in the Southeastern USA can be adapted to fulfill both the demand for wood products and for bioenergy. This study quantifies the impact of plantation management choices on the cumulative carbon balance and the net present value of loblolly pine plantations at the stand level, as well as the wood supply cost for bioenergy production for these different management strategies. The strategies assessed (conventional, additional thinning and short rotation) are characterised by planting density, thinning age and rotation period, each with and without collection and utilization of slash residues for bioenergy. The total wood supply costs for bioenergy include the cultivation, harvesting and transport costs for small diameter trees and slash. The results show that the carbon balance after 100 years is 205 (247), 214 (268) and 149 (195) Mg ha^{-1} for the conventional, additional thinning, and short rotation loblolly pine plantation management strategies (within parentheses: same strategies with slash utilization). The conventional strategy has the lowest wood supply costs for bioenergy, 47 (46) \$ Mg^{-1} pulpwood, followed by the additional thinning strategy, 50 (49) \$ Mg^{-1} pulpwood, and 54 (52) \$ Mg^{-1} pulpwood for the short rotation management strategy. In conclusion, switching from the current conventional strategy without the utilization of slash for bioenergy to an additional thinning strategy with the use of slash increases the overall carbon accumulation by about 31%, at marginally higher wood supply cost. Adapting plantation management strategies can have a positive effect on the economic performance and on the carbon balance of loblolly pine plantations. Integration of wood supply for bioenergy and traditional forestry sectors can lead to co-benefits in terms of cost reduction and carbon accumulation.

1. Introduction

The anthropogenically driven increase in atmospheric concentrations of greenhouse gasses (GHG) is considered to be the key driver of human induced climate change [1]. The utilization of bioenergy, potentially in combination with CO_2 capture and storage, is considered an important GHG emission mitigation option [1,2]. Softwood plantations in the Southeastern United States of America (USA) are recognized as potential biomass feedstock to meet the domestic as well as transatlantic demand for bioenergy [3–5]. Currently, harvested softwood is used to produce a variety of timber products in the Southeastern USA, including sawtimber, pulpwood, veneer logs, plywood, industrial fuel, and other wood products [6]. With an increasing interest in fossil fuel displacement, there is a growing potential demand for (low-cost) biomass feedstock.

Today, a common softwood management strategy in the Southeastern USA is tailored to produce a mix of sawtimber- and pulpwood-size wood in a rotation period of around 25 years [3]. Harvested softwood in the Southeast is classified according to the minimal diameter of the tree at breast height (d.b.h.) and the minimal top diameter. Commonly, three main wood classes are distinguished, from small to larger diameters: pulpwood (PW), chip-n-saw (CNS)[1] and sawtimber (ST) size wood. Bark and lignin is already used for energy in wood processing facilities. For large-scale bioenergy production smaller trees, trees not suitable for wood products, and harvesting residues are being proposed, or are already used for bioenergy [3]. Plantation management strategies can be altered to maximise the production of bioenergy feedstock. This may include increased planting density, additional thinning, and/or shortening the rotation period to increase annualised wood production per hectare [3,7]. However, changes to the

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[1] Medium-sized tree logs harvested to produce small lumber and chips for pulpwood.

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plantation management for the enhanced production of bioenergy from forest biomass has raised concerns over the loss of carbon stocks and the temporal imbalance between carbon release and uptake [8]. Furthermore, adapting the plantation management strategy may result in higher cultivation and/or harvestings costs [3]. Given the existing wood industry in the Southeastern USA, the anticipated increased harvests for bioenergy production in this region face a number of challenges that may limit the production of bioenergy. First, the utilization of forest plantations for bioenergy should provide a net reduction in GHG emissions compared to current conventional management practices. Second, the total bioenergy production cost should be economically competitive with other (renewable) energy sources and other land uses.

The use of softwood, especially the native loblolly pine (*Pinus taeda* L.), in commercial wood plantations in the Southeastern USA is often justified by foresters by emphasizing the high yield of merchantable wood on a wide range of sites [9]. Loblolly pine yield is very responsive to plantation management practices: positive impacts on diameter growth rate and biomass accumulation are widely reported [10–13]. The softwood plantation management choices (e.g. fertilization or planting density) also affects the merchantable volume of sawtimber, chip-n-saw and pulpwood, as discussed by various publications [14–19]. The carbon uptake by tree growth, sequestration in wood products and carbon displacement by material substitution is reported by various other publications [20–23]. Finally, the impact of wood utilization (including bioenergy) on carbon accumulation has also been investigated [8,23–26].

As illustrated by Dwivedi and Khanna [14], the optimal rotation period to maximise economic profit is defined by the site quality and plantation management intensity. Dickens and Will [16] concluded that increasing planting density may increase wood yield, however, the disparity in price between pulpwood, chip-n-saw, and sawtimber suggests there is an optimal planting density to maximise net benefit. A high planting density with additional thinning is only economically viable if harvested trees reach merchantable diameter [16]. Many studies have evaluated the economics or GHG emission performance of bioenergy production in the USA (see e.g.: Cardoso, Özdemir, and Eltrop [29]; Hoefnagels, Junginger, and Faaij [27]; Pirraglia, Gonzalez, and Saloni [30]; Trømborg et al. [28]. Generally, the total bioenergy production costs (excluding distribution) are dominated by the total biomass delivery costs [31–33].

As indicated above, the expected increase in wood harvest for bioenergy is likely to affect the carbon balance and economic performance of forestry plantations. The studies mentioned above, however, only focus on either the economic performance or carbon balance of plantation management strategies, consider bioenergy as a solitary industry, or neglect the displaced GHG emissions due to product substitution. A detailed and simultaneous quantification of the carbon balance and economic performance can contribute to more informed decision making about embedding the increasing bioenergy demand in the current forestry sector. Such assessment for different plantation management strategies is important for the selection of the optimal strategy in terms of economics and carbon accumulation given the expansion of demand for bioenergy. Accordingly we evaluate the carbon balance and economic performance of three different loblolly pine plantation management regimes in the Southeastern USA for the production of wood pellets alongside conventional wood products. The cultivation, harvest and transport costs and net carbon balance are evaluated with and without the utilization of slash for bioenergy for several wood productivity classes at thinning or final harvest.

2. Materials and methods

2.1. General approach

The aim of this study is to quantify the impact of plantation management choices on the GHG and economic performance of bioenergy production using loblolly pine in the Southeastern USA. Therefore, the cumulative carbon balance and the net present value of a loblolly pine plantation is calculated on a per hectare basis as well as calculating the wood supply cost for bioenergy production for different management strategies. The plantation management strategies affect both the overall yield of the loblolly pine plantation as well as the composition of the yield in terms of different wood product classes (sawtimber, chip-n-saw, pulpwood and slash). It is assumed that 80% of the harvested pulpwood is utilized for pulp and paper production, and that the other 20% is used for bioenergy production. Slash wood (logging residues) are the otherwise un-merchantable tops and branches of the harvested trees and is considered as optional bioenergy feedstock, similar to [34].

The following sections describe the different steps taken to determine the total carbon balance and economic performance of different plantation management strategies. To illustrate the dynamics of the carbon accumulation over time, the carbon balance is calculated for an individual stand over 100 years.

2.2. Plantation management strategies

The loblolly pine plantation management strategies assessed in this study are named “conventional” (C), “additional thinning” (AT) and “short rotation” (SR). See Table 1 for the characteristics of each plantation management strategy. The *conventional* management strategy represents a currently applied management strategy that yields a mix of sawtimber, chip-n-saw and pulpwood, in a rotation of 25 years with a thinning in year 15, as described by Perlack and Stokes [3]. The *short rotation* management strategy defined here, involves a rotation period of 16 years with a high planting density to attain high biomass accumulation. To enable a high yield level, the application of fertilizers and agrochemicals is higher compared to the conventional strategy [35,36].

Table 1
Silvicultural plantation management practices of the three plantation management strategies.

Management item	Plantation management strategies (abbreviation)		
	Conventional[a] (C)	Short rotation (SR)[b]	Additional thinning[c] (AT)
Site prep intensity	Medium	High	High
Planting density (trees per hectare)	1500	3000	3000
Herbicide, year of application	1	1 & 3	1 & 3
P-fertilization as DAP in kg ha^{-1} (year of application)	17.5 (4 & 8)	22 (4 & 6)	22 (4, 10 & 15)
N-fertilization as urea in kg ha^{-1} (year of application)	155 (4 & 8)	199 (4 & 6)	199 (4, 10 & 15)
Thinning, year of application (thinning intensity[d])	15 (30%)	No	10 (50%) 15 (30%)
Harvest, year of application	25	16	25

[a] Presently, a common loblolly pine management strategy [3].

[b] A management strategy with high initial planting density, no thinning, and early clear-cut harvest, similar to [35].

[c] A management strategy to maximise volume growth by increased planting density and early thinning, as described by Ref. [7].

[d] The thinning intensity describes the percentage of (live) trees harvested during thinning.

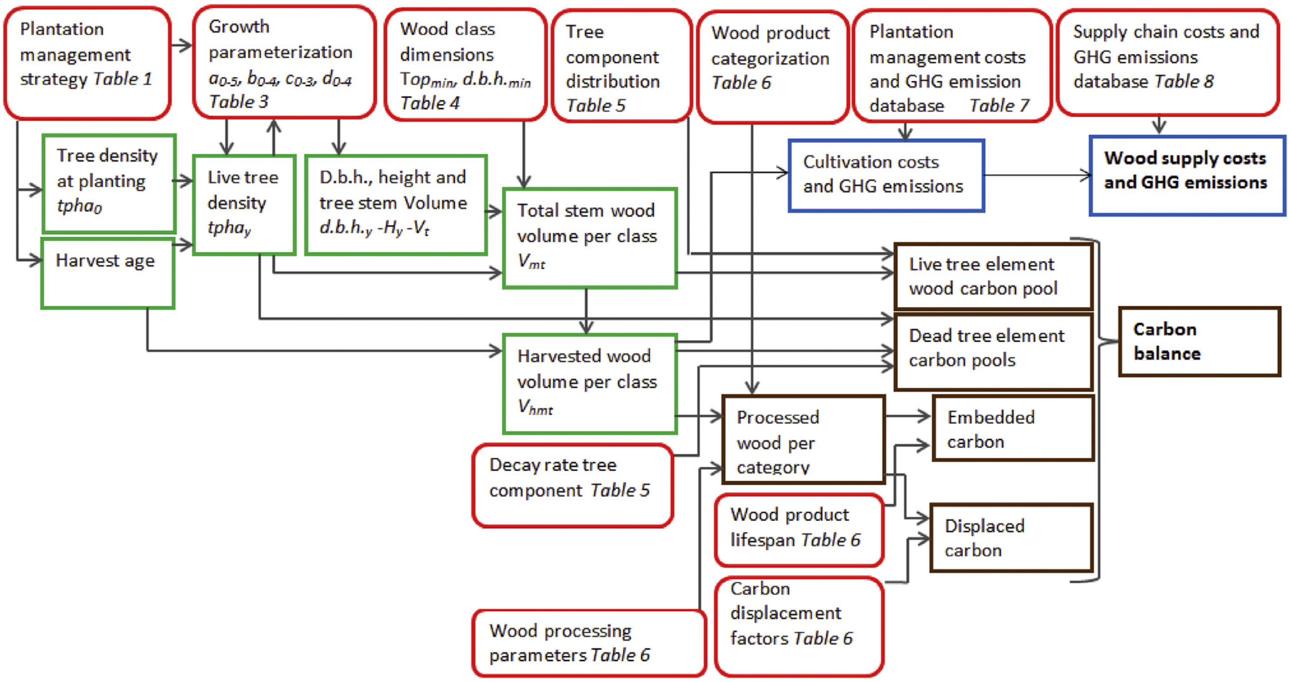

Fig. 1. Schematic overview of the structure used to determine the dynamic carbon balance and economic performance of different loblolly pine plantation management strategies in the Southeastern USA. Red-lined shapes are input parameters, green lined squares calculate the harvested wood volume per class, blue squares calculate the wood supply costs and the brown shapes calculate the total dynamic carbon balance. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

The *additional thinning* strategy has an increased planting density in combination with a thinning in year 10 and year 15 of the 25 year rotation, to yield a high amount of pulpwood [3]. For each management strategy, a sub-strategy is defined that includes the collection and utilization of 'slash' for bioenergy production.

2.3. Model framework

A model is constructed to calculate the total carbon balance and carry out the economic analysis of the different loblolly pine plantation management strategies. A visualisation of the data input, calculation steps and final results in this analysis is shown in Fig. 1. The characteristics of the plantation management strategies define the tree growth parameters, which in turn determine the diameter, height and mass growth curve. The development in individual tree mass and the number of live trees determine the total wood mass per hectare for each year of the rotation period. The mass growth curve of loblolly pine trees and the harvested wood classes are key inputs for the calculation of the in-situ and ex-situ carbon pools of each plantation management strategy. The mass growth curve determines the live tree carbon pool. The decaying wood carbon pools are based on the tree mortality and tree component distribution. The tree component distribution describes the mass distribution of total tree mass over fine-, coarse-, and taproots, stem wood, stembark, branches and foliage. The harvested wood is categorised in four wood product categories (long, medium-long, medium-short, and short-life wood products), each with a specific processing efficiency, displacement factor, and wood product lifespan.

As the economic values of the harvested wood classes differ significantly, the total plantation management costs are economically allocated to the different wood classes harvested. Adding the harvesting, collection and transport costs to the (allocated) cultivation costs of loblolly pine results in the total delivery costs of pulpwood size wood or slash wood. In particular, the harvesting costs may differ between different plantation management strategies, due to the difference in harvesting equipment capacity resulting from the differences in tree diameter and tree mass at the time of harvest.

2.4. Growth of loblolly pine trees

The modelling of total wood yield and classification into pulpwood, chip-n-saw and sawtimber-size wood is simplified to five growth equations. First, the tree survival rate is determined, which is based on the soil quality, initial tree density and plantation age, see Equation (1), derived from Ref. [37]. The diameter at breast height (d.b.h.) and total tree height are determined with Equations (2) and (3), assuming a typical S-shaped growth curve, similar to Scott and Tiarks [7]. The diameter and height are used to determine the average individual tree mass (to merchantable top diameter), similar to [37], see Equation (4). Combining the tree mass (Equation (4)) and tree survival (Equation (1)), the total wood mass per hectare in each rotation age is determined. Finally, the total wood mass is classified into sawtimber, chip-n-saw, pulpwood, and slash-size wood using the individual wood class dimensions for d.b.h. and top diameter (top_{minwc}), see Equation (5), similar to [38]. To determine the quadratic mean diameter ($d.b.h._q$) and the diameter of pulpwood size trees, a normal distribution of tree diameters is considered, based on the diameter distribution shown in Ref. [11].

$$tpha_t = a_0 + \left[(tpha_i - a_0)^{-a_1} + a_2^2\, a_3\left(t_t^{a_4} - t_i^{a_4}\right)\right]^{-\frac{1}{a_1}} \tag{1}$$

$$d.\ b.\ h._t = b_0\left[1 - e^{-b_1 b_2 t}\left[1 - (b_3)^{-b_1}\right]\right]^{-\frac{1}{b_1}} \tag{2}$$

$$H_t = c_0\left[1 - e^{-c_1 c_2 t}\left[1 - (c_3)^{-c_1}\right]\right]^{-\frac{1}{c_1}} \tag{3}$$

$$V_t = d_0 d.\ b.\ h._t\ .^{d_1}\ d_2 H_t^{d_3} \tag{4}$$

$$V_{mwct} = tpha_t V_t\left[-e_0\left(\frac{top_{\min wc}}{d.\ b.\ c._q}\right)^{e_1} - e_2\frac{tpha_t}{2.47}^{-e_3\left(\frac{d.b.h._{\min wc}}{d.b.h_q}\right)^{e_4}}\right] \tag{5}$$

Variable	Description	Unit
$tpha_t$	Number of trees per hectare at age t of plantation	ha^{-1}
$a_0 - a_4$	Tree survival parameters (regression analysis)	[−]
$tpha_i$	Number of trees per hectare at planting or given age i	ha^{-1}
i	Initial age (0) or given age i	a
t	Age of plantation	a
$d.b.h._{(t)}$	Diameter at age *t*	cm
$b_0 - b_3$	D.b.h. growth parameters (regression analysis)	[−]
$H_{(t)}$	Height at age *t*	m
$c_0 - c_3$	Height growth parameters (regression analysis)	[−]
$V_{(t)}$	Stem mass per tree at age t	Mg
$d_0 - d_3$	Mass growth parameters (regression analysis)	[−]
V_{mwct}	Merchantable mass of specific wood class (wc) at age t	Mg ha^{-1}
$e_0 - e_4$	Mass classification parameters (regression analysis)	[−]
top_{min}	Minimal top diameter wood class (wc)	cm
$d.b.c._q$	Quadratic diameter based on diameter at breast height	cm
$d.h.b._{min}$	Minimal diameter at breast height of a wood class (wc)	cm

2.5. Carbon balance

The total carbon balance dynamics of the plantations in this study include: the GHG emissions in the wood supply chain, carbon in live trees, carbon in dead trees, embedded biogenic carbon in final wood products, and avoided fossil GHG emissions by product substitution. The avoided (fossil) GHG emissions show the GHG emissions, expressed as carbon equivalent extracted from the atmosphere. Wood supply chain GHG emissions include all fossil GHG emission associated with plantation management, harvesting and transport. Based on the tree stem mass growth (see section 2.4) and the tree component distribution, the total carbon sequestered by live trees is determined for both below-as well as aboveground tree elements. The dead tree carbon pool includes dying trees (based on Equation (1)) and the residual tree components left in the plantation after thinning or final harvest. For each tree component, a specific decay rate is taken into account as small debris decays faster than large debris. The decay rate is defined as the fraction of decaying wood that turns into atmospheric carbon per year [22]. To account for the embedded carbon in wood products, each harvest is categorised into four product categories, each category with a specific wood processing efficiency and product lifespan. As the use of wood products substitutes the use of alternative products (steel, concrete, etc.) a carbon displacement corresponding to the wood category is considered. The carbon displacement expresses the carbon displaced by wood product use over the use of other materials, similar to the definition of [39]. The total dynamic carbon balance is determined for several plantation management cycles, and expressed as Mg carbon per hectare (Mg ha^{-1}). Based on this dynamic trend, a linear trend line is plotted (trend line for 100 year period). Given the differences in rotation length of the strategies, this line enables comparison at every time point despite differences in stand age and differences in stored carbon at that age.

2.6. Total wood supply costs of loblolly pine

2.6.1. Cultivation costs of loblolly pine

The cultivation costs are determined using Equation (6), which include the allocation of plantation management costs. According to the wood class prices, the factor *f* represents the economic allocation factor of each wood class. In other words, this factor *f* is the economic value of the wood class yield divided by the total economic value of the harvested wood.

$$Biomass\ cultivation\ cost_{wc} = \frac{\sum_{t=1}^{t=ht} \frac{\sum_{n=1}^{N}(O_{ny} \times C_{ny} \times f_{wc})}{(1+a)^y}}{\sum_{t=1}^{t=ht} \frac{V_{mwct}}{(1+a)^t}} \tag{6}$$

Item	Description	Unit
Biomass cultivation $costs_{wc}$	Discounted cultivation costs of wood class	\$ Mg^{-1}
O_{ny}	Occurrence cost item per ha_n in year t	#
C_{ny}	Costs of item n in year t	\$ ha^{-1}
F_{wc}	Economic allocation factor of wood class	[−]
V_{mwct}	Merchantable mass of wood class in year t	Mg ha^{-1}
a	Discount rate	% a^{-1}
t	Age of the rotation	a
ht	Year of final harvest	a

2.6.2. Harvesting and transport of pulpwood and biomass

The harvesting costs include all costs associated with felling, skidding and loading loblolly pine trees at thinning age or at final harvest. Costs for harvest operations found in previous research are simplified to hourly operational costs and multiplied by hourly capacity of the machines. Hourly operation costs are commonly determined by considering the investment costs, lifetime, utilization rate, fuel consumption, lube and oil costs and labour wages [40–42]. Only for felling is the hourly productivity linked to tree diameter, as felling small diameter trees reduces productivity significantly [43]. Equation (7) describes the felling costs for loblolly pine trees. To determine the total transportation costs, both fixed and variable transport costs are considered.

$$Felling\ costs = \frac{Hourly\ cost \times (a \times d.\ b.\ h.)}{V_{mwct}} \tag{7}$$

Item	Description	Unit
Felling costs	Biomass felling costs	\$ Mg^{-1}
Hourly cost	Hourly operational costs of harvesting machinery	\$ h^{-1}
a	Felling time per diameter of the tree stem	h cm^{-1}
d.b.h.	Diameter breast height	cm
V_{mwct}	Tree mass at harvesting age t	Mg

2.7. CO_2 abatement costs

Carbon dioxide abatement costs are calculated for the plantation management strategies using the difference in both the total carbon balance and the plantation management costs compared to the conventional strategy. This approach is adapted from the carbon dioxide abatement costs approach found in Ref. [44]. The carbon abatement costs are expressed in \$ per Mg CO_2 (\$ Mg^{-1}) using Equation (8).

$$CO_2\ abatement\ costs = \frac{\sum_{y=1}^{y=100} \frac{\sum_{n=1}^{N}(V_{mwct} \times (BCC_n - BCC_c))}{(1+a)^y}}{(C_n - C_c)} \times \frac{44}{12} \tag{8}$$

Item	Description	Unit
CO_2 abatement costs	Costs for CO_2 abatement expressed per Mg carbon dioxide	$\$ Mg^{-1}$
V_{mwct}	Merchantable mass of specific wood class (wc) at age t	$Mg\ ha^{-1}$
BCC_n	Biomass cultivation costs of strategy *n*	$\$ Mg^{-1}$
BCC_c	Biomass cultivation costs of the conventional strategy	$\$ Mg^{-1}$
a	Discount rate	$\%\ a^{-1}$
y	Year of the rotation period	a
C_n	Linear carbon balance after 100 year of strategy *n*	$Mg\ ha^{-1}$
C_c	Linear carbon balance after 100 year of the conventional strategy	$Mg\ ha^{-1}$
3.665	Molar mass ratio of CO_2 to the atomic mass of carbon	–

2.8. Sensitivity analysis

A sensitivity analysis provides information on the robustness of the results by varying the key input parameters used in this analysis to determine total carbon balance and cultivation costs. The diameter growth curve, mass growth curve, displacement factors, difference between displacement factors, price of wood classes, the difference in price between wood classes and discount rate have an a priori expectation to affect the result to a large extent and are therefore included in the sensitivity analysis. The diameter growth and individual tree mass growth curve are key intermediate results, as shown in Fig. 1. The diameter growth also impacts the wood classification and affects the total mass growth, and thereby, indirectly affects the carbon balance and economic performance. The variation in tree mass growth, while the wood classification remains unchanged, is designed to show the impact of increased yield without variation in wood classification (and subsequently no change in carbon displacement factors for these classes). The potential impact of soil quality, availability of water, nutrient availability and other factors are partly captured by the tree diameter growth variation. Changes in tree diameter growth impact the tree mass and the classification of harvested wood. The price of sawtimber, chip-n-saw and pulpwood affects the allocation of plantation management costs to the different wood classes and thereby influences the economic performance. The displacement factors are important for the carbon balance over time, especially over longer time frames. The included variables and the parameter variation are presented in Table 2.

3. Data input

3.1. Growth parameters and wood allocation

For each year of the plantation rotation cycle, the growth and wood yield Equations (1)–(5) are used to determine the total wood mass per harvested wood class. Details of the growth input parameters used in Equations (1)–(5) are presented in Table 3.

To determine the merchantable mass of sawtimber, chip-n-saw and pulpwood size wood, the minimal dimensions of each wood class as presented in Table 4 are used in Equation (5). In this analysis, only the minimal diameter at breast height ($d.b.h._{min}$) and the minimal top

Table 2
Sensitivity analysis parameter, range of variation and affected result.

	Parameter variation %	Cultivation costs	Carbon timeline
Diameter growth parameter b_0	± 20[a]	X	X
Tree volume	± 35[b]	X	X
Price difference between pulpwood and sawtimber	± 20[c]	X	
Displacement factor variation	± 50[d]		X
Variation in the difference between displacement factors used for the different wood categories	± 50[d]		X

[a] By changing the management intensity (with similar planting density and site quality) a d.b.h. difference up to 20% is reported by Ref. [45]. Therefore, a 20% variation in parameter b_0 is taken into account.

[b] Total wood volume difference between operational and intensive management reduces with age (when not thinned) [45]. As the youngest harvest age is 10 year, the associated difference is considered at this age, 32% [45], as basis for the tree volume variation taken into account in this sensitivity analysis.

[c] In the recent decade timber prices for pulpwood, chip-n-saw and sawtimber have follow a similar trend (TimberMart South) with variation in the difference between pulpwood and sawtimber prices being limited. The observed variation in the price difference over the time period 2011–2016 is approximately 15%, in this analysis a variation of 20% is taken into account.

[d] As shown by the meta-analysis of Sathre and O'Connor [39] a large variation in displacement factors is found in the literature; between −2.3 and 15 kg kg^{-1} of carbon (depending on wood product type and studied supply chain). This variation includes unlikely product substitutions, the most common displacement factors are in the range of 1.0 to 3.0 kg kg^{-1} [46].

Table 3
Parameterization for loblolly pine growth determined with Equations (1)–(5).

	Trees per hectare ($t.p.h.a._t$)	Diameter breast height ($d.b.h._y$)	Height (H_t)	Tree volume (V_t)	Wood class volume of the tree (V_{mt})
	a[a]	b	c[b]	d[c]	E[d]
0	247	−2.77 × LN (t.p.ha.) + α[e]	25	0.1823	−1.0344
1	−0.74534	0.037[f]	0.013	1.826	3.9498
2	0.0003425	α + β x $t.p.h.a._t$[g]	11	0.006214	−5.0629
3	50	8 or 10[h]	0.06	1.22196	−0.37045
4	1.9747	–	–	–	6.0046

[a] To model the tree survival rate, a survival prediction equation is considered, for which the parametrization is taken from Ref. [37], using a lower asymptotic survival of 494 trees per ha (value a_0) [37].

[b] The impact of planting density on the height growth curve is limited [47]. Therefore, no relationship between tree density and height for the different management strategies is considered in this analysis.

[c] The stem volume parameters are directly taken from Harrison and Borders [37], and are specific for loblolly pine growth (inside bark) in the Lower Coastal Plain of the Southeastern USA.

[d] The parameters used in Equation (5) are obtained from Ref. [38], based on work of [48].

[e] A natural logarithmic relationship between the planting density and the growth parameter a_0 is used, based on the data provided in the planting density study of Pienaar, Shiver, and Harrison [47].

[f] Since a relationship between diameter growth parameter b_1 and planting density on diameter growth is not evident, a universal value of 0.037 is considered, which matches the growth increase of the diameter found in Ref. [47].

[g] A linear relationship between planting density and growth parameter b_2 is used to model the diameter growth, similar to the growth curve found in Pienaar et al. [47]. Values of −0.00002 and 0.0656 are considered for α and β respectively, derived from Pienaar et al. [47].

[h] To match the growth curve specified in Ref. [47] for different planting densities a value of 8 is considered for tree survival parameter a_3, however, to consider the influence of vegetation control on wood yield a value of 11 is considered for the short rotation management strategy.

Table 4

Softwood classifications for harvested wood classes.

Classification[a]	Diameter at breast height range (cm)	Minimal top diameter (cm)	Average price ($ Mg^{-1})[b]
Slash	7.5–11	2.5	11
Pulpwood	11–19	11.4	24
Chip-and-saw	19–29	15.2	42
Sawtimber	> 29	17.8	64

[a] The wood class ‘slash’ is included for the plantation management strategies that include slash utilization.

[b] Average price is based on the timber price of the last five years (2012–2017), as presented by Ref. [49].

diameter (top_{min}) are considered. Table 4 also presents the economic value of the different wood classes, this enables the economic allocation of softwood plantation management costs to the individual harvested wood classes.

3.2. Carbon balance, in-situ and ex-situ

The mass distribution and decay rates to determine the carbon of the different live or dead tree components, are shown in Table 5. Both the above- and belowground tree mass is further distinguished into smaller tree components, all with a specific decay rate when left in the field after harvest or death. To determine the ex-situ carbon pools (embedded and displaced carbon) the wood processing efficiency, lifespan of wood products, and displacement factors are specified (see Table 6). Both slash and pulpwood are considered as potential feedstock for wood pellet production, aimed at fuel for power plants in Northwestern Europe. The displacement factors are directly taken from literature and expressed as the amount of fossil carbon displaced by carbon embedded in wood products (Mg Mg^{-1}). The displacement factors include the processing of wood into wood products and the reference products. However, these carbon displacement factors do not include the carbon emissions related to landfilling of wood products after use. Sathre and O'Connor [46] found that landfilling of wood products has a very limited effect on the displacement factors.

3.3. Plantation management costs and GHG emission

Costs and GHG emissions of loblolly pine plantation establishment and maintenance are collected from various publications. Table 7 presents an overview of silvicultural practices and their associated costs and GHG emissions, along with the background information. A discount rate of 4% is considered for the economic analysis [18,19]. A detailed overview of the plantation management practices per strategy is shown in the supplementary information, Table S1.

Table 5

Mass distribution and decay rates of loblolly pine tree components.

	Component	Mass fraction of live trees (%)	Decay rate (% a^{-1})[c]
Below ground biomass (22%)[a]	Fine roots	1.8[b]	15
	Coarse roots	4.4[b]	12
	Tap roots	15.8[b]	10
Above ground biomass (78%)[a]	Stemwood	60.1[d]	10
	(Stem)bark	6.4[d] [e]	10
	Branches	7.3[d]	12
	Foliage	3.8[d]	15

[a] Accordingto Samuelson et al. [13], below ground biomass represents approximately 22–25% of total tree mass in young pine stands.

[b] The totalbelowground biomass is distributed over tap roots (75%), coarse roots (18%) and fine roots (8%) based on [13].

[c] Reported decay rates for foliage, coarse woody debris, and lateral roots are 15, 12 and 10% mass loss per year, respectively [22]. These values are utilized for thick stemwood and tap roots, branches and coarse roots or foliage and fine roots.

[d] Above ground tree component distribution are based on values reported by Subedi [50] [51].

[e] (Stem) bak is approximately 8.5% of total aboveground biomass [52].

Table 6

Wood processing efficiency, distribution of harvested wood classes to wood product categories and carbon displacement factors for the different wood classes.

		Wood class			
		Sawtimber	Chip-n-saw	Pulpwood	Slash
Wood conversion efficiency (%)		65%[a]	65%[a]	58%[a]	78%[c]
Wood product category (lifespan)	Long (50 years)	50[a]	25[a]	0[a]	0
	Medium-long (16)	25[a]	25[a]	0[a]	0
	Medium-short (4)	0[a]	0[a]	33[a]	0
	Short (1)	25[a]	50[a]	67[a]	100[b]
Displacement factor (kg kg^{-1} of carbon)[d]		2.1	1.8	1.5	0.5[e]

[a] The proportion of wood class to harvested wood product categories and the conversion efficiencies are based on wood product characteristics as specified by Gonzalez-Benecke et al. [22].

[b] In this analysis, it is assumed that the collected slash is fully utilized for bioenergy production, and therefore classified as a short lifespan wood product category.

[c] The mass conversion of harvested carbon to mass of pellets is 1.56 (we assume that the carbon mass fraction in the pellet is that same as that in the wood i.e. 50 %).

[d] The carbon displacement factor range for common wood products is between 1.0 and 3.0 kg kg^{-1}, with a wood product average of 2.1 kg kg^{-1} [39,46]. Sawtimber can be used for a variety of timber products, whereas pulpwood can only be used for a small selection of wood products. Therefore, the displacement factors are varied in this analysis, similar to the study of Pingoud, Pohjola, and Valsta [53].

[e] For the utilization of slash for bioenergy (wood pellets for electricity) this analysis considers an electrical energy carbon dioxide equivalence comparator of 198 g MJ^{-1} [54].

3.4. Wood delivery costs

Table 8 lists the costs and GHG emissions of harvest operations for softwood harvesting. The harvesting system includes a feller-buncher, grapple skidder, pre-processor and loading station. Although the felling costs for a feller-buncher are higher compared to chainsaws, the total harvesting system productivity and costs for the whole harvesting system are lower [43].

4. Results

4.1. Wood yield

The calculated wood yield per wood class for the different loblolly pine plantation management strategies in the Southeastern USA are shown in Fig. 2. The dry wood yield is expressed in Mg ha^{-1} a^{-1}. In general, increasing plantation density and fertilizer application rate increases annual wood yield, especially for the short rotation management strategy. However, this management strategy yields very little sawtimber and chip-n-saw size wood. This is a result of the reduced diameter growth at higher planting densities and the early harvest age. The conventional and additional thinning strategy yield similar amounts of sawtimber and chip-n-saw size wood. However, due to the increased planting density the first and second thinning yield almost exclusively pulpwood-size wood and slash. The slash yield is higher for

Table 7

Costs and GHG emissions of loblolly pine plantation management practices.

Function	Main equipment	\$/quantity	CO_2eq./quantity
Site preparation	Shear, rake and pile	$175\ \$\ \mathrm{ha}^{-1}$[a]	$167\,\mathrm{kg\ ha}^{-1}$[b]
	Bedding	$370\ \$\ \mathrm{ha}^{-1}$[c]	$202\,\mathrm{kg\ ha}^{-1}$[d]
Planting	Mech. planting	$310\ \$\ \mathrm{ha}^{-1}$[e]	$109\,\mathrm{kg\ ha}^{-1}$[f]
Aerial application agrochemicals	Helicopter	$31\ \$\ \mathrm{ha}^{-1}$[g]	$28\,\mathrm{kg}_{q}\ \mathrm{ha}^{-1}$[h]
Herbaceous weed control	Backpack	$45\ \$\ \mathrm{ha}^{-1}$[i]	$62\,\mathrm{kg\ ha}^{-1}$[j]
Seedlings (per 1000 seedlings)		$75\ \$$[k]	27 kg [l]
Fertilizers	DAP	$464\ \$\ \mathrm{Mg}^{-1}$[m]	$2.03\,\mathrm{kg\ kg}^{-1}$[n]
	Urea	$273\ \$\ \mathrm{Mg}^{-1}$[o]	$5.15\,\mathrm{kg\ kg}^{-1}$[n]
Herbicide	Velpar ULW	$70\ \$\ \mathrm{ha}^{-1}$[p]	$62\,\mathrm{kg\ ha}^{-1}$[j]

[a] Total site preparation (including bedding) is 199 $\$\ \mathrm{acre}^{-1}$ (original unit in reference) [38], to calculate the shear, rake and piling costs, the costs for bedding is subtracted from the total site preparation costs.

[b] Using a desel consumption of $43\,\mathrm{L\,ha}^{-1}$ for site preparation [55] and a GHG emission intensity of $3.89\,\mathrm{kg\ CO}_{2\ eq}\ \mathrm{L}^{-1}$ of diesel is based on total carbon emission intensity of $24.1\,\mathrm{g\,C\,MJ}^{-1}$ diesel [56] and Higher Heating Value of diesel of $44\,\mathrm{MJ\,L}^{-1}$, [57].

[c] Bedding costs were based on the costs for bedding in the Southern Coastal Plain in 2012, [58].

[d] A diesel consumption of $52\,\mathrm{L\,ha}^{-1}$ is considered for a tractor with bedding plow, based on [55], combined with the GHG emission intensity of diesel as specified under footnote B.

[e] Although hand planting may be less expensive, in this analysis the use of mechanized planting is considered at a costs of 139.45 $\$\ \mathrm{acre}^{-1}$, typical for the Southeastern USA [58].

[f] Diesel consumption of a skidder with tree planter is $28\,\mathrm{L\,ha}^{-1}$ [55].

[g] The hourly operational costs of a helicopter are specified as 1200 $\$\ \mathrm{hour}^{-1}$ [59] and the time occupation is estimated as $0.023\,\mathrm{h\,ha}^{-1}$ [55], in line with cruising speed and the width of a spray boom of a helicopter.

[h] Helicopter fuel use is $9\,\mathrm{L\,ha}^{-1}$, based on [55], and a GHG emissions intensity of $3.081\,\mathrm{kg\,CO}_{2eq}\,\mathrm{L}^{-1}$. The GHG emission intensity of jet fuel is based on the direct combustion emissions of $2.529\,\mathrm{kg\,CO}_{2eq}\,\mathrm{l}^{-1}$ [60] and supply chain GHG emissions of $15\,\mathrm{g\ CO}_2\ \mathrm{MJ}^{-1}$ [61], heating value of $46.2\,\mathrm{MJ\,kg}^{-1}$ and density of $0.802\,\mathrm{kg\,L}^{-1}$, based on [60].

[i] Chemical treatment with herbicides to control woody and herbaceous weeds using a backpack sprayer is based on [58].

[j] The application of herbicides has a total GHG emission intensity of 62 kg $CO_2\ \mathrm{ha}^{-1}$ (including production of herbicides), similar to [62].

[k] The costsfor seedlings may range between 57 and 420 $ per 1000 seedlings [63], in this analysis costs per seedling are assumed to be 0.075 $ per seedling, similar to [18].

[l] GHG emissions associated with the seed orchard, nursery and transport to the plantation (total of 40.92 kg CO_2 for 1500 seedlings [64]) is recalculated to 0.027 kg CO_2 per seedling delivered to a loblolly pine plantation.

[m] Price of DAP considered for August 2015, based on [67], with DAP contents of approximately 22% phosphorus.

[n] Data retrieved from Ref. [66], GHG emissions include production but also application phase.

[o] Price of urea considered for August 2015, based on [65], with urea contents of approximately 44–46% nitrogen.

[p] Herbicideapplication, excluding equipment for distribution, based on [38].

the additional thinning and short rotation management strategy due to the early thinning or harvest, as younger trees yield relatively higher amounts of slash.

4.2. Carbon timeline of loblolly pine management strategies

Fig. 3 visualizes the four in-situ and ex-situ carbon pools for the conventional management strategy (for simplicity the supply chain GHG emissions are left out here) to illustrate the build-up of the total carbon balance over several rotations. The live biomass carbon pool shows a typical growth curve, interrupted by a thinning and final harvest at the end of each rotation. The thinning and harvest are followed by an increase of the dead carbon pool, which slowly decays over time. Over the rotation cycle, the dead carbon pool increases due to tree mortality. After the lifespan of the longest product life (i.e., 50 years), equal amounts of carbon in harvested wood products are added and removed from the embedded biogenic carbon pool, resulting in a stable carbon pool. However, the displaced carbon increases with each harvest, as with each harvest fossil GHG emissions are avoided due to product substitution.

In Fig. 4, the total dynamic carbon balance and the linear carbon trend lines of the different plantation management strategies are shown. The increasing trend of the total carbon balance is due to cumulative fossil carbon displacement, while the oscillating curve is due to the tree growth cycles. The difference in harvest age between the conventional and short rotation strategy is clearly shown (Fig. 4). The total carbon stocks after 100 years are 205 (247), 214 (268) and 149 (195) $\mathrm{Mg\ ha}^{-1}$ for the conventional, additional thinning and short rotation management strategies (in the parentheses is the same strategies with the additional use of slash for bioenergy). However, when considering the linear carbon trend lines, the carbon stock after 100 years is 237 (267), 242 (284) and 211 (258) $\mathrm{Mg\ ha}^{-1}$ for the conventional, additional thinning and short rotation plantation management strategies, respectively. Interestingly, the short rotation strategy with and without slash utilization accumulates high amounts of carbon in live and dead wood. However, the conventional and additional thinning strategies displace more carbon due to wood product use. Therefore, the dynamic (and linear) carbon trend of these strategies surpassed the short rotation strategy shortly after initiation, as seen in Fig. 4. Important to note is the influence of the composition of wood yield on the total carbon balance. For example, the wood yield of the short rotation management strategy is higher than the other strategies, however, it yields mainly pulpwood size material, which has a lower displacement factor than sawtimber and chip-n-saw wood classes (see Table 6). There is a similar difference between the conventional and the additional thinning strategy; the additional thinning strategy produces more wood, but the amount of sawtimber and chip-n-saw wood is (slightly) higher for the conventional strategy, resulting in a higher displacement of fossil carbon.

4.3. Economic performance of loblolly pine management strategies

Consistent with expectations, increased plantation density and fertilization is associated with higher total plantation management costs, resulting from increased seedling density, fertilizer use and herbicide application. For all management strategies, the land costs are the largest share of the total plantation management costs (see Table SI2). Fig. 5 shows the total delivery costs of pulpwood-size wood for the different plantation management strategies, distinguishing the contribution of land, cultivation, harvest and transport costs. The conventional strategy has the lowest wood supply costs (47 and 46 $\$\ \mathrm{Mg}^{-1}$), followed by the additional thinning strategy (50 and 49 $\$\ \mathrm{Mg}^{-1}$), and the short rotation management strategy (54 and 52 $\$\ \mathrm{Mg}^{-1}$) (without or with slash use). Using no product allocation (instead of economic allocation), total pulpwood delivery costs increase to 54–60 $\$\ \mathrm{Mg}^{-1}$. This small increase (46–54 versus 54–60 $\$\ \mathrm{Mg}^{-1}$) of wood delivery costs is due to increased cultivation costs (not allocated to different wood classes) but lower harvest costs per dry Mg wood due to larger average d.b.h. of trees. The loblolly pine delivery costs of pulpwood in this study can be broken down into land (17–22%), plantation management (15–22%), harvesting (25–31%) and transport (31–37%).

In Fig. 5, the additional thinning strategy has the lowest pulpwood cultivation costs (17.9 and 16.6 $\$\ \mathrm{Mg}^{-1}$), followed by the conventional strategy (17.9 and 17.3 $\$\ \mathrm{Mg}^{-1}$) and the short rotation management strategy (21.5 and 19.6 $\$\ \mathrm{Mg}^{1}$), although the differences between the different plantation management strategies are small.

Table 9 presents the (theoretical) abatement costs; a metric to show

Table 8
Costs and GHG emissions of Loblolly pine harvesting equipment.

Function	Main equipment	Capacity (Mg $hour^{-1}$)	\$ $unit^{-1}$	CO_2eq./quantity
Felling	Feller buncher	Variable[a]	130 \$ h^{-1}[b]	88 kg h^{-1}[c]
Skidding	Grapple skidder	30 Mg h^{-1}[s]	105 \$ h^{-1}[e]	118 kg h^{-1}[f]
Loader	Loading station	60 Mg h^{-1}[g]	125 \$ h^{-1}[h]	118 kg h^{-1}[f]
Transport	Truck with trailer	–	11.7 \$ Mg^{-1}[i]	12.5 kg Mg^{-1}[J]
Slash collection	Slash collection with skidder	30 Mg h^{-1}[d]	16 \$ Mg^{-1} [k]	3.93 kg Mg^{-1}[l]

[a] The capacity of a feller buncher is strongly related to the tree diameter for a diameter range between 12 and 37 cm (5–15 inch) [43].

[b] Based on the high capacity feller buncher, as described in Ref. [35].

[c] Assuming diesel consumption of 22.7 L per Productive Machine Hour (PMH) [55] and a GHG emission intensity of 3.89 kg $CO_{2\text{-eq}}$ L^{-1} of diesel production and consumption, footnote B of Table 5.

[d] Skidder capacity may vary according to tree volume, skidding distance and slope of the terrain. In this analysis a skidder productivity of 30 Mg ha^{-1} is considered, based on [35].

[e] Based on the high capacity skidder, as described in Ref. [35].

[f] A diesel consumption of 30.3 L h^{-1} is considered for the skidder as well as the loader.

[g] Assuming a high loader, as described in Ref. [35].

[h] Capacity of a tree loader, based on [32,35].

[i] Based on 2015 fixed and variable truck transportation costs of 4.32 \$ Mg^{-1} and 0.134 \$ $Mg^{-1}km^{-1}$ respectively [35].

[j] Using a diesel consumption of 0.69 L $load^{-1}$ km^{-1} [29,68], GHG emission intensity diesel and empty returns using 40% of diesel compared to loaded trip [69].

[k] Collection of slash residues and delivery to in-forest landing place, based on [70].

[l] Using thefuel consumption of a skidder, 30.3 L h^{-1} [62], and the averaged capacity of 30 Mg h^{-1}, based on [35].

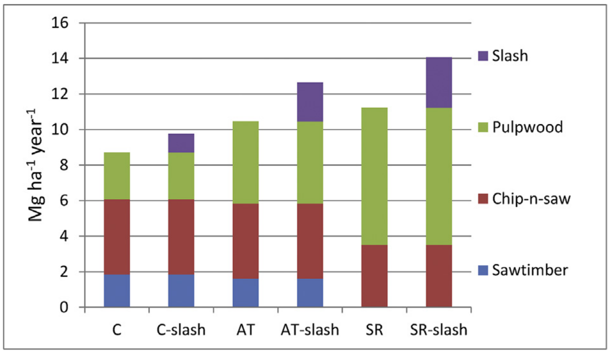

Fig. 2. Wood class yield for the conventional (c), additional thinning (AT) and short rotation (SR) loblolly pine management strategies, expressed in Megagram wood per hectare per year.

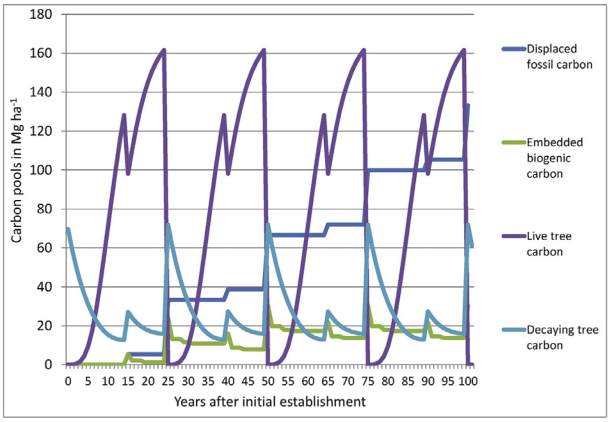

Fig. 3. Dynamics of in-situ and ex-situ carbon pools of a loblolly pine plantation given a conventional management strategy.

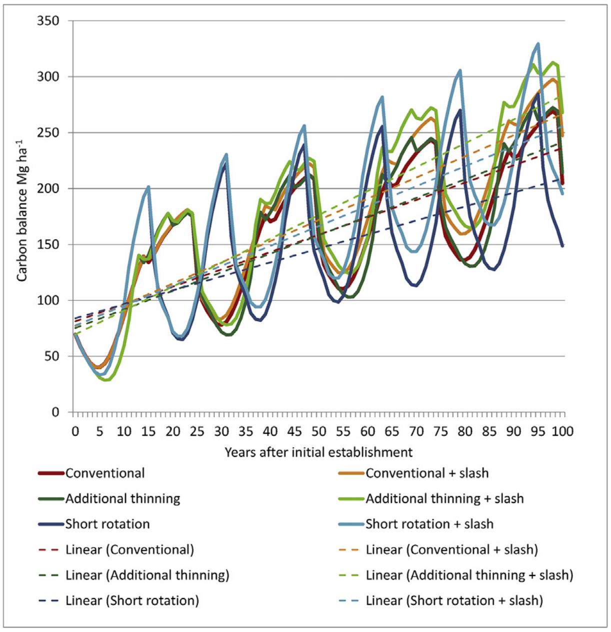

Fig. 4. Total carbon balances of the conventional, additional thinning and short rotation plantation management strategies, with and without the utilization of slash, including linear trend line.

the additional costs for a plantation management strategy and the additional carbon sequestration compared to the conventional strategy. The short rotation strategy without slash utilization has no higher carbon accumulation compared to the conventional strategy and is therefore excluded from the abatement costs analysis. Furthermore, not all strategies have higher cultivation costs or higher carbon balance compared to the conventional strategy. This results in negative carbon dioxide abatement costs for the conventional with slash strategy, additional thinning strategies and the short rotation strategy with slash. In other words, these strategies (e.g., slash harvest) could sequester more carbon for the same total cost. Only for the short rotation with slash strategy, the carbon abatement costs are positive as more carbon is sequestered after 100 years but at higher costs compared to the conventional strategy.

4.4. Sensitivity analysis

The sensitivity analysis was performed for the linear carbon balance (100 years) and the pulpwood supply costs of the different plantation management strategies (Figs. 6 and 7). The diameter growth has the largest impact on the total carbon balance, followed by the impact of tree mass growth. Both factors have an impact on growth of pine trees and subsequently on yield and the embedded and displaced carbon. The

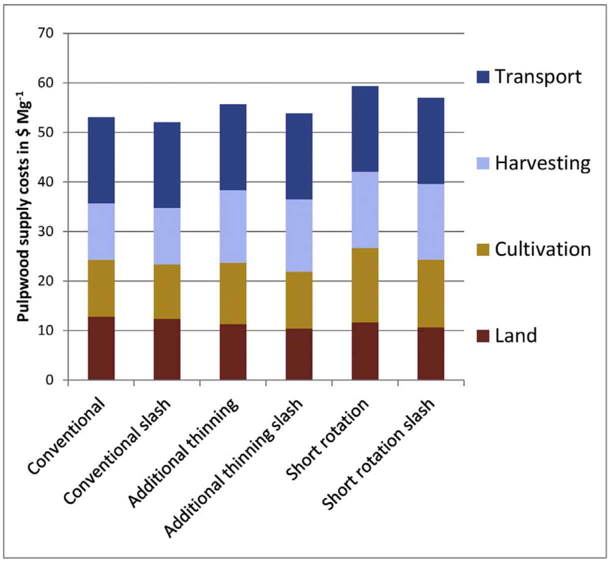

Fig. 5. Total pulpwood supply costs of the selected loblolly pine plantation management strategies in the southeastern US, separated by land, cultivation, harvest and transport costs.

diameter increase is especially important as it has a high impact on yield but also on the wood classification, which results in a higher displacement factor for trees with a larger d.b.h.

The cultivation costs of pulpwood are also sensitive to the diameter variation as it impacts the wood yield and wood classification. Tree mass has an impact on the wood yield and therefore impacts the cultivation costs, especially at lower mass yields. The impact of the price difference and discount factor is lower compared to the tree mass and diameter variation (Fig. 7).

5. Discussion

This study evaluated the total carbon balance and economic performance of loblolly pine plantation management strategies in the Southeastern USA producing bioenergy feedstock. As such, these results are specific for loblolly pine stands in this growing region but the approach may well inform other intensively managed plantation systems.

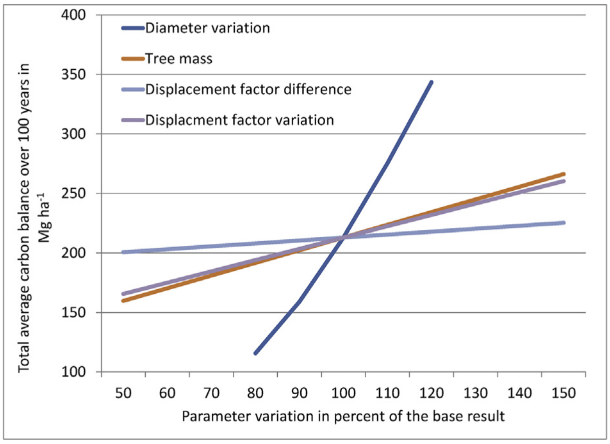

Fig. 6. Sensitivity analysis for the total carbon accumulation after 100 years using the linear trend, for the conventional plantation management strategy when varying diameter growth, tree volume growth, displacement factors and the difference between considered displacement factors.

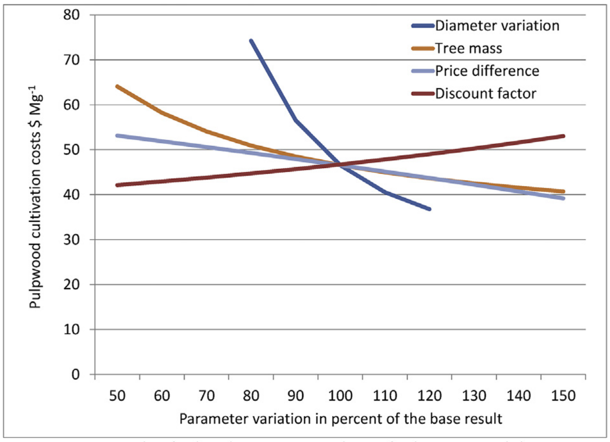

Fig. 7. Sensitivity analysis for the pulpwood wood supply costs for the conventional plantation management strategies when varying diameter growth, tree volume growth and the price difference of the wood classes considered in this study.

Table 9
Wood yield, cultivation costs and GHG emissions of pulpwood and slash production for different plantation management strategies in the Southeastern USA.

		Unit	Conventional	Conventional slash	Additional thinning	Additional thinning slash	Short rotation	Short rotation slash
C-balance	Year of the rotation age	Mg ha^{-1}	176	178	175	178	201	201
	Year after rotation age	Mg ha^{-1}	121	137	125	141	138	150
	Dynamically after 100 years	Mg ha^{-1}	205	247	214	268	149	195
	Dynamically after 200 years	Mg ha^{-1}	307	387	324	429	247	353
	Linear trend line after 100 year	Mg ha^{-1}	237	267	242	284	211	258
Costs	Allocated pulpwood cultivation costs	\$ Mg^{-1}	17.92	17.32	17.86	16.60	21.49	19.57
	Allocated slash cultivation costs	\$ Mg^{-1}	–	8.66	–	8.03	–	9.78
	Total pulpwood supply costs	\$ Mg^{-1}	47	46	50	49	54	52
	Total slash supply costs	\$ Mg^{-1}	–	42	–	41	–	43
GHG emissions	Allocated GHG emissions pulpwood	kg CO_{2eq} Mg^{-1}	3.81	3.69	3.75	3.48	7.21	6.56
	Allocated GHG emissions slash	kg CO_{2eq} Mg^{-1}	–	1.84	–	1.69	–	3.28
	Total (fossil) GHG emission of wood supply	kg CO_{2eq} Mg^{-1}	27.22	27.23	29.43	29.17	33.38	32.73
NPV	Plantation NPV	\$ ha^{-1}	686	748	777	997	65	264
	CO_2 abatement costs	\$ Mg CO_{2eq}^{-1}	–	−8	−7	−13	-	21

Pulpwood delivery costs reported for loblolly pine by other studies are in the range of 40–73 \$ Mg^{-1} [35,73], while slash delivery is between 24 and 60 \$ Mg^{-1} [70,73]. This is in line with the cost breakdown of pulpwood supply costs reported by others [35,70,73]. In comparison, hypothetical production of switchgrass in the Southeastern USA has cultivation costs in the range of 40–70 \$ Mg^{-1} [38], while reported total delivery costs are in the range of 55–87 \$ Mg^{-1} [74]. Thus, from an economic perspective, a combined production of biomass for wood products and energy seems favourable over producing 100% energy crops.

Currently, slash is not used for wood pellet production, mainly due to the low quality of the feedstock as slash is often contaminated with mineral soil and has a high ash content. Slash could, however, be used as boiler fuel (e.g. saw mills), substituting more high-quality residues such as sawdust and shavings, which in turn could then be used for wood pellet production.

Although the difference between the price of pulpwood and the cultivation costs is small in some cases, all plantation strategies provide a profit margin compared to the average price of pulpwood.

Accurately predicting diameter growth in response to management, particular changing planting density, is critical to robustly estimating tree mass growth and product class. Average tree growth is based on five growth equations, using this simplified approach may result in an under- or overestimation of the growth of the total stand. Modelled growth of the trees is dependent on diameter, which is a key variable in the tree mass growth. Diameter affects tree size as well as the wood product classification. Although the diameter growth parametrization is based on a somewhat older study [47], a more recent analysis [45] showed a similar diameter growth curve as simulated in the current analysis. However, the parametrization of the growth equations used for this study were based on empirical data for lower planting densities. For higher planting densities, more empirical data to enable better parametrization would be preferred. Furthermore, there is a risk that harvested wood is classified wrongly due to over- or under estimating the diameter. However, a comparison of wood class yield with another study shows similar results for the distribution of pulpwood, chip-n-saw and sawtimber wood [14].

Especially for simulation periods of 100 years and longer, the carbon balance is dictated by the carbon displacement due to product substitution, in contrast to the stabilizing biogenic carbon embedded in wood products. The study of [71] also illustrated the high share of displaced carbon in the overall carbon balance, especially over longer time periods. The displacement factors included in this study are taken from the extensive review of displacement factors by Sathre and O'Connor (2010). The main issue with the use of generic carbon displacement factors is the lack of data regarding wood processing, utilization of wood products, product lifespan and end-of-life disposal of wood products [72]. Due to this lack of data the carbon displacement factors used in this study are uncertain.

For bioenergy, the carbon displacement factor is based on the average EU electricity mix but when considering a displacement factor based on coal powered electricity the carbon accumulation can be higher, especially for the short rotation strategy. Studies excluding the displacement of fossil carbon concluded that (for longer time frames) live trees are the largest carbon pool with only a limited share of embedded (biogenic) carbon, especially when producing short lifespan wood products [20,22]. Excluding the displaced fossil carbon in the total carbon balance favours longer rotation periods for the production of sawtimber, as it is generally assumed this wood class is processed to longer lifespan wood products.

Despite these uncertainties, including the carbon displacement factors demonstrates the potential impact of different wood class yields outside the forest plantation. Therefore, it provides a better picture of the impact of plantation management decisions on the overall carbon balance.

The most prominent difference between the different plantation management strategies is the yield of sawtimber and chip-n-saw wood. Especially for the additional thinning and conventional strategies, the allocation of a large proportion of the plantation management costs to sawtimber and chip-n-saw reduces the costs for pulpwood or slash. The product allocation is based on the classification of tree sizes, which is done with a general merchantable mass equation developed some decades ago [75] but is still applied in recent publications [15,76]. Therefore, using this approach is considered a reasonable approach to classify the harvested wood, although the amount of merchantable wood is sensitive to the diameter at harvest age t. Furthermore, the utilization of slash in the sub-management strategies increases the total wood yield and thereby reduces the allocated cultivation costs for all wood classes.

As also shown in Figure SI.2 the ranking of preferred plantation management strategy does not change when varying an economic parameter; only the difference changes slightly. The economic performance is very sensitive to the diameter growth curve. For the classification in this study, only sawtimber, chip-n-saw, pulpwood and slash are considered, other wood classes like pole trees, veneer logs and others are included in sawtimber, even though these could hold higher economic value for the wood processing industry. When considering more wood classes with a higher economic value, more costs can be allocated to these classes, potentially reducing the production costs of pulpwood further. On the other hand, it remains to be seen how the quality of sawtimber and chip-n-saw products is affected by higher planting densities.

Finally, this paper solely focuses on the changing economic and GHG performances of changing management strategies. Other aspects, such as overall environmental impacts (e.g. on biodiversity, requirements to meet sustainable forest management criteria) and socio-economic impacts (e.g. possibly additional job creation) were not considered.

6. Conclusion

In this study, the total wood yield per hectare ranged from 8.7 to 14.1 $Mg\,ha^{-1}\,y^{-1}$, with the highest total yield for the short rotation management strategy with slash utilization. Wood yield, however, was not per se the best criteria for the selection of plantation management strategies to accumulate carbon or attain the lowest wood supply costs.

This study concluded that switching from a current conventional plantation strategy without slash harvest to an additional thinning strategy with using slash for bioenergy increases the potential wood supply for GHG emission reduction (31% more carbon accumulated over a 100-year period). This increase requires only a marginally higher wood supply cost (approximately 1.8 \$ Mg^{-1}). The total wood supply costs of the different plantation management strategies are in the range of 46–54 \$ Mg^{-1} (2.7–3.2 \$ GJ^{-1}) and 41–43 \$ Mg^{-1} slash (2.4–2.5 \$ GJ^{-1}).

Furthermore, in the cases of conventional plantations with slash harvest, additional thinning, and additional thinning with slash harvest, abatement cost for CO_2 were all negative. This suggests that more CO_2 could be accumulated at a lower cost. The present study supports the conclusion that increased plantation management can have a positive effect on the economic performance as well as the carbon balance of loblolly pine plantations in the Southeastern USA. Furthermore, the integration of woody bioenergy use and the traditional forestry sectors leads to co-benefits in terms of cost reduction and carbon accumulation, especially for longer timeframes.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.biombioe.2018.06.017.

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