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Carbon payback period and carbon offset parity point of wood pellet production in the South-eastern United States

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Abstract

This study examines the effect of methodological choices to determine the carbon payback time and the offset parity point for wood pellet production from softwood plantations in the South-eastern United States. Using the carbon accounting model GORCAM we model low-, medium- and high-intensity plantation management scenarios for a single stand level, an increasing stand level and a landscape level. Other variables are the fossil-fuel reference system and the electrical conversion efficiency. Due to the large amount of possible methodological choices and reference systems, there is a wide range of payback times (≤ 1 year at landscape to 27 years at stand level) and offset parity points (2–106 years). Important aspects impacting on the carbon balances are yield, carbon replacement factor, system boundaries and the choice of reference scenario used to determine the parity point. We consider the landscape-level carbon debt approach more appropriate for the situation in the South-eastern United States, where softwood plantation is already in existence, and under this precondition, we conclude that the issue of carbon payback is basically nonexistent. If comparison against a protection scenario is deemed realistic and policy relevant, and assuming that wood pellets directly replace coal in an average coal power plant, the carbon offset parity point is in the range 12–46 years; i.e. one or two rotations. Switching to intensively managed plantations yields most drastic reduction in the time to parity points (≤ 17 years in 9 of 12 cases).

Keywords: bioenergy, carbon debt, carbon parity offset, carbon payback, Wood pellets

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Introduction

The use of biomass for energy and materials is considered an essential alternative to fossil fuel consumption, thereby reducing GHG emissions (Chum *et al*., 2011). To stimulate bioenergy consumption, different policies have been implemented around the world. Wood pellet consumption in Europe, for example, is mainly for residential heating, district heating and large-scale power production. The international trade of wood pellets is triggered by demand-side policies. Extra-EU trade of wood pellets is mainly with Canada, the United States of America (USA) and Russia. In recent years the export of wood pellets from the United States have increased rapidly, mainly due to the large production capacity increase in the South-eastern United States, to meet the demands of the European market (Lamers *et al*., 2012). Our analysis focuses on the use of forestry biomass for wood pellet production. Forests are essential for both the large storage of carbon and the exchange (flux) of carbon with the atmosphere (Ingerson, 2007).

The conversion of biomass into energy will not by default generate sustainable bioenergy. According to Cherubini *et al*. (2009), the greenhouse gas balance of bioenergy systems is subject to differences in feedstock, conversion technology, end-use technology, system boundaries (fossil-fuel) reference system and regional differences. Sustainably produced bioenergy can reduce or avoid the GHG emissions from fossil fuels (Chum *et al*., 2011). Next to the overall greenhouse gas balance, carbon stock change induced by the use of biomass for energy have increasingly become part of public debate (including the time required before organic carbon released by combustion is recaptured through the uptake by plants). The carbon payback time of forestry biomass was already treated by Schlamadinger & Marland (1996) in a study that compared different bioenergy crops, including the conversion of mature forest and agricultural land into bioenergy plantations. More recent publication include, among others, Colnes *et al*. (2012), Walker *et al*. (2010), Zanchi *et al*. (2010), McKechnie *et al*. (2011), Mitchell *et al*. (2012) and Holtsmark (2012).

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The study by Zanchi *et al.* (2010) provides insights into the carbon neutrality of different bioenergy production systems. The carbon neutrality is based on the difference between the carbon emissions (or avoided emissions) of a bioenergy system compared with a fossil fuel system. Zanchi *et al.* (2010) reports results showing that the carbon payback period of short rotation forestry that has displaced high carbon stock mature forests can be as long as 150 years. Mitchell *et al.* (2012) provides a conceptual explanation on the difference between carbon payback and carbon parity point. The carbon payback period is the period between initial harvest and the point in time were the overall carbon balance equals the carbon storage before initial harvest, taken into account carbon debt and avoided fossil fuels. The carbon parity point is the time between initial harvest and the point in time when the utilization of forestry biomass is favourable over the reference scenario, again considering the carbon debt and (avoided) fossil fuel emissions (Mitchell *et al.*, 2012). Walker *et al.* (2010) found that the carbon payback period is 21 years when forestry biomass–based electricity is compared with electricity produced from coal, and more than 90 years for electricity produced from natural gas for a case study in Massachusetts. The carbon payback period was defined as the time period before the cumulative carbon flux of a bioenergy system equals a fossil-fuel reference system, taking into account a carbon debt for the bioenergy system. Essential variables are the (re) growth of biomass and fossil fuel emissions. The assessment of McKechnie *et al.* (2011) found similar results; after 17–38 years wood pellet electricity production is beneficial over coal fired power from a greenhouse gas viewpoint. McKenzie plots the (decrease in) forest carbon stock while substituting fossil fuels at the same time. Mitchell *et al.* (2012) provides insights into the carbon payback period and the carbon offset parity point of forest bioenergy. Mitchell *et al.* (2012) concluded that the initial landscape conditions and land-use history were of major importance to the carbon payback period. The results range from a carbon payback period of 1 year for ‘Post-agricultural landscapes’ to 19–1000 years for ‘Old-growth landscapes’, the latter one due to the high carbon stocks before the initial harvest. Low carbon payback periods and low carbon offset parity points are reached with high yields and low initial carbon stock (before first harvest; Zanchi *et al.*, 2010; Mitchell *et al.*, 2012).

In the study of Holtsmark (2012), the typical life cycle of a spruce tree (growth phase, 100 years; mature stable phase, 100 years; standing dead tree, 30 years; decaying downed dead wood, 100 years) is seen as the basis for the long carbon payback periods. The study results indicated a carbon payback period of 190 years for woody biomass from a boreal forest replacing coal in power plants (Holtsmark, 2012). The study used a larger area (landscape level) to determine the payback periods; in which the biomass regrowth and avoided emissions were important parameters. A study by Colnes *et al.* (2012) found that the atmospheric cumulative carbon balance is favourable after 35–50 years when utilizing forests in the South-eastern United States and thereby substituting different fossil fuel sources. Colnes *et al.* (2012) used a landscape-level approach in their cumulative atmospheric carbon balance. The study focussed on supplying current and potential future bioenergy projects with existing plantations.

The studies addressed above used different methodologies to assess the carbon debt pay-off period of bioenergy systems, compared with fossil-fuel reference systems. Next to the methodology (and methodological choices) the model input parameters are of influence as well, as discussed earlier. No studies were found that determined the carbon payback period and carbon parity point for fast-growing softwood plantations using different methodological approaches. The goal of this research is to establish carbon balances of wood pellet production in the South-east of the United States of America and subsequent cofiring in large-scale power plants, using stemwood (including thinnings) from softwood plantations, utilizing different methodologies. This case study will gain insight into the carbon payback time and carbon offset parity point of forestry biomass and methodological choices and issues related to forestry carbon balances. The case study analysis includes all major components of the carbon balance, including forest carbon pools, CO_2 equivalent emissions of silviculture practices, transportation emission and emissions related to pelletizing. The avoided fossil fuel emissions have also been taking into account. Given the increase in wood pellet demand in European countries we included an analysis of more intensive plantation management, including the related GHG emissions of silvicultural practices and the supply chain emissions.

As advocated by Searchinger *et al.* (2009), the greenhouse gas emission profile of bioenergy depends on the type of biomass feedstock used and land-use change effects caused by the land claim for feedstock production. The review of Johnson (2009) showed that since 1992, numerous studies have been published on carbon accounting of bioenergy production systems. Schlamadinger and Marland have been used by IEA task 38 and the UNFCCC (2003). As early as 1996, Schlamadinger & Marland (1996) performed a carbon analysis of 16 bioenergy production system scenarios, varying from an ‘ethanol from corn’ scenario to ‘afforestation of agricultural land’ or a ‘continuing conventional forestry’ scenario. Schlamadinger & Marland (1996) found that with high growth rates and efficient use of harvested wood, the highest reduction in carbon emissions is with fossil fuel displacement. With lower growth rates or less efficient use of harvest material, the differences in final use (traditional forest products, bioenergy or no harvest) of the carbon balance is similar at a 100-year time frame. Forestry carbon pools include; soil carbon, tree carbon, other vegetation carbon, dead wood carbon and carbon in litter. Many different forest carbon accounting models exist, for example the FORCARB2 model (Heath *et al.*, 2009), CO2FIX (Masera *et al.*, 2003), EFISCEN (Nabuurs *et al.*, 2000), GORCAM (Schlamadinger & Marland, 1996) and CBM-CFS3 (Kurz *et al.*, 1992). The examples of carbon models pointed out here use forest inventories or empirical growth curves to determine forest carbon stocks (and subsequent carbon fluxes; Kurz *et al.*, 2009).

In recent studies different tools were used to determine the forestry carbon pools. Colnes *et al.* (2012) used the FVS-SN (Forest Vegetation Simulator-Southern Variant) to estimate the forest (re) growth and other forest carbon pools. The results are compared with the emissions of fossil fuels on a landscape level. McKechnie *et al.* (2011) adapted the FORCARB model to the region-specific conditions for a temperate forest in Ontario, Canada. The results of this study were plotted as CO_2 pools, using a landscape-level approach. Mitchell *et al.* (2012) used also a landscape-level approach to show the impact of harvest intensity and rotation length on the carbon payback time and time before the carbon parity point is reached. The studies referred to here all used different harvest scenarios.

In section 2, the methodology for the case study is shown. Section 3 provides an overview of measures to increase yields and related GHG emissions during silvicultural practices. The fourth section provides the overall carbon balances of the different carbon balances using different carbon accounting approaches. Section 5 presents the CO_2 emissions profile of wood pellet fired electricity using an approach suggested by the European Commission. Section 6 is the discussion section.

Materials and methods

In our study, the GORCAM carbon accounting model is utilized to determine carbon stocks and stock changes of forest carbon in softwood plantations in the South-eastern United States. An important feature of the GORCAM model is the ability to vary input parameters; to adjust the carbon accounting model to a region-specific case, while remaining user friendly at the same time. Among others, Schlamadinger & Marland (1996) and Zanchi *et al.* (2010) used the GORCAM model to determine forest carbon fluxes, including harvested carbon for bioenergy production. A detailed description of the GORCAM model structure and input parameter is shown in Schlamadinger & Marland (1996). Schlamadinger & Marland (1996) also provides an overview of 16 different bioenergy production systems and its carbon balance over time.

In our analysis, we determine the carbon balance of whole-tree harvesting for wood pellet production, using different methodological approaches, under different management intensities. The stand-level, increasing stand-level and landscape-level approaches are utilized for the different management intensity scenarios. This will gain insight into the potential effect of the different approaches. The intended results will show the carbon payback periods and carbon offset parity point of the different scenarios. All relevant input parameters for the GORCAM are shown as supplementary appendix.

A *stand-level approach* considers a 1 ha forest plot which is harvested completely at year 0, and harvested again at the end of the rotation period. In the results, the typical tree (re) growth curve is clearly depicted in the results using a stand-level approach. An *increasing stand-level approach* considers the harvest (and replant) of a forest plot each year. Important to note is that the carbon debt is considered at the harvest (and not at year 0), until the first harvested plot is harvested for the second time for bioenergy production. See Fig. 1, a 25 ha plot with annual harvest; each year a new carbon debt is added to the total carbon debt. Therefore, utilizing an increasing stand-level approach, the carbon debt increases over time, until the next (consecutive) harvest. Considering a *landscape-level approach*, or a forest plot with uneven-aged (ranging in age from 0 to 25 years for low management intensity and 0–20 years for high management intensity) trees to enable annual harvest, the forest carbon pools are averaged (Berndes *et al.*, 2011). This would result in a stable ecosystem carbon level (assuming no change in forest management) throughout the modelling period, assuming an equal amount of forest plots compared with the years of one rotation.

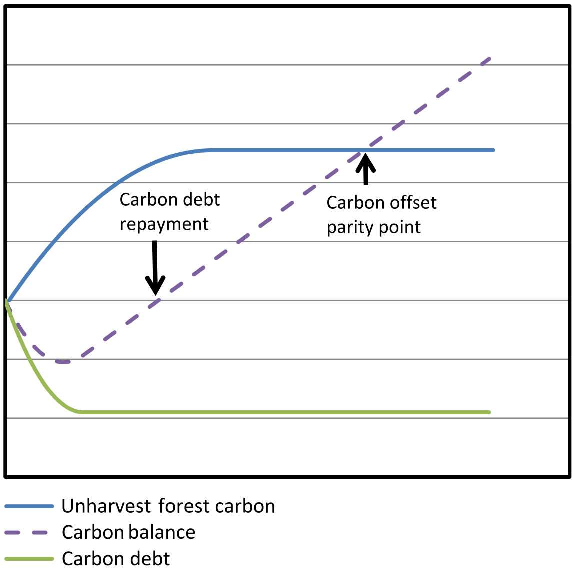

Fig 1 Visual representation of the carbon payback period and the carbon offset parity point on a stand level, taken from Mitchell *et al.* [2012].

The plantation can be seen as part of the bioenergy supply chain, and therefore the whole supply area should be incorporated into the carbon balance. In other words, the plantation is part of the integrated supply chain. On the other hand, it can be argued that the plantations are independent to the wood pellet supply chain, and there is a choice for using it, (a) for energy, (b) for timber, pulp or other wood products or (c) not using them at all. We have developed a 'no-harvest' and a 'natural regrowth' scenario in which the plantations are not harvested or replanted after harvest; in this way, the softwood plantation could serve as carbon sink, a potential carbon mitigation strategy. These – to a certain extent hypothetical – scenarios are used when determining the carbon offset parity point. The 'no-harvest scenario' has the same starting point compared with the productive scenarios. Within both scenarios only the additional growth over the starting point (year 0 of modelling) is considered. The 'natural regrowth' scenario is developed to determine the carbon stock of a naturally regenerated forest plot; a longleaf pine forest plot (van Deuzen & Heath, 2011). All approaches used are expressed on a per hectare basis to allow easy comparison.

Case study

The states of Florida, Georgia, North Carolina, South Carolina and Virginia of the United States were selected as sourcing region for the case study. These states form the South-eastern United States of America and were considered to be representative of a potential sourcing region to supply the European wood pellet market. Forest land is a prominent land use in the South-eastern region of the United States. Of the Southern region, roughly 60% is categorized as forested land. More than 97% of the forested land is labelled as timberland. Areas qualifying as timber land are capable of producing in excess of 20 cubic feet per acre (1.40 m^3 ha^{-1}) per year of industrial wood in natural stands. In 2007, almost 86% of the timberland was privately owned; this category includes the forest industry, other corporate or individual and family owned forests (Smith *et al.*, 2009). Of the area classified as timberland, 26% is stocked with loblolly-shortleaf pine and 12% is stocked with longleaf-slash pine. The age of softwood timber land is dominantly in the age class 0–19 years and 19–39 years of age, indicating recent clear-cut harvest.

A large fraction of the forested area in the Southern United States is actively managed to provide pulpwood, construction wood and other wood products. Southern forests provide around 18% of the global pulpwood and 7% of global industrial round wood demand, whereas Southern forest cover only 2% of the total forested area in the world (Hanson *et al.*, 2011). Since 1950, the planted pine category increased from less than 1–7 million ha in 1999, largely at the expense of naturally regenerated pine (Wear & Greis 2002). Both the ownership class and forest management type are indications of timberland ownership objectives, for example, planting is seen as an upfront investment for commercial wood production (Butler & Wear, 2011). In the Southern United States, Best Management Practices (BMP's) were developed to minimize the environmental impact of intensive harvesting and site preparation, for example, soil erosion and offsite movement of sediment (Fox *et al.*, 2004). For example, in Georgia the latest version of the Georgian BMP was developed to 'establish sound, responsible, guiding principles for silviculture operations' (GFC, 2009). Despite the voluntary character of the BMP principles, compliance is high in Southern pine silviculture (Fox *et al.*, 2004).

The GORCAM model is utilized to determine the forest carbon flows in South-eastern softwood plantations, where whole softwood trees are harvested for wood pellet production. The forest carbon modelling is extended with an inventory of fossil carbon emissions throughout the supply chain; including silvicultural emissions, transport emissions, pelletizing emissions and avoided fossil fuel emissions in the European power plants. The fossil-fuel reference system is coal fired power plants in North-western Europe. All carbon emissions in the supply chain are recalculated per scenario on a per hectare basis for the overall carbon balance and to enable comparison between scenarios.

In the South-eastern United States of America the potential to increase areal yields (Alavalapati *et al.*, 2011) and the structural change in timber and paper and pulp demand (Wear *et al.*, 2011) could support increased wood pellet production without land-use change. Therefore, the possible effect of direct and indirect land-use change is not taken into account. The wood pellets are produced from softwood plantations, which would otherwise be utilized for timber or paper and pulp production. When calculating the carbon balance, a carbon debt is taking into account. The carbon debt here is defined as the forest carbon stock affected by initial harvest, and is considered as a negative carbon flux.

For the case study three different forest management scenarios were evaluated:

- The first scenario was the low management intensity scenario, with limited site preparation, planting and a clear-cut harvest after 25 years.
- The second scenario included more intensive forest management practices in the softwood plantations: more intensive site preparation, planting, fertilization at age 3 and after thinning, a midrotation thinning at age 15 and clear-cut harvest at age 25.
- The third scenario is the most intensive forest management. As the goal is to maximize annual yield, this scenario includes intensive site preparation, planting, fertilization around planting and at ages 5 and 12, herbicide application before planting, and at age 1. A thinning is performed at age 12, followed by a clear-cut harvest at age 20.

Both the softwood from thinnings and clear-cut harvest are used for wood pellet production.

Input parameters for the GORCAM carbon accounting model are based on forest carbon inventory data, scientific publications, expert opinion and other relevant publications. Yield estimations are derived from Fox *et al.* (2004), Stanturf *et al.* (2003), Borders *et al.* (2004) and Kline & Coleman (2010). Greenhouse gas emissions of transport, silviculture emissions and pelletizing emissions are based on scientific publications, such as Markewitz (2006), Uasuf (2010), Sikkema *et al.* (2010) and Magelli *et al.* (2009), and emission databases, such as the EcoInvent database.

Soil carbon

Soil carbon represents a large carbon pool in forestry. Important input for the soil carbon stock is the humification of downed dead vegetation. Removing (harvesting) residues is likely to reduce mineral carbon in soils, due to the reduced input from decomposing material (Peckham & Gower, 2010). As soil carbon stocks are not monitored, estimations are based on broad forest types (Ingerson, 2007). A review and meta-analysis of the effect of harvesting on carbon sequestration, described in Skog & Stanturf (2010), found that generally harvesting had no or little effect on soil carbon; whereas whole-tree removal showed a slight decrease in soil carbon. The meta-analysis of Nave *et al.* (2010) found that in temperate forests around the world harvesting reduces soil carbon on average, the variation was mainly caused by tree species, soil taxonomic order and time since harvest (recovery of carbon pools). Limited data were found on the soil carbon levels under different management intensities. Colnes *et al.* (2012) expected no significant changes in the soil carbon pool between the different end-use scenarios. Furthermore, Colnes *et al.* indicated the lack of accurate carbon models to model the soil carbon (change). In this research, the COLE (Carbon On Line Estimator; van Deuzen & Heath, 2011) is used to gain insight into the soil carbon pools of softwood plantations. In case of reforestation the soil organic carbon value is constant, based on the assumption that soil carbon will remain constant over time (van Deuzen & Heath, 2011). Furthermore, the COLE database describes no soil carbon change due to higher management intensity (USDA, 2011). Based on this database and available literature (as described above) no soil carbon loss is assumed in our study, as stumps and harvesting residues are left on site. Even for a thinning; a silvicultural practice to yield biomass by removing every third (or fifth) row and off-size trees to enable further growth of the remaining trees, the tops and branches are left on site.

Truck transport

In this case study we assume an average distance from softwood plantation to wood pellet plant of 100 km (single trip). An emission factor for 16–32 tonne trucks was used (Spielmann *et al.*, 2007). For empty return trips, emissions are reduced by 60% compared with loaded trucks (Hamelinck *et al.*, 2005). To express the GHG emissions as emission per tonne pellets, the amount of green tonnes transported per tonne of wood pellets needs to be determined. Throughout the supply chain, dry matter is lost during feedstock handling, pelletizing and during handling in export ports and during oceanic shipment (Sikkema *et al.*, 2010). Consistent with Sikkema, a dry matter loss of 7% is assumed to account for the total dry matter loss in the supply chain from plantation to power plant. Next to dry matter loss, the feedstock required for drying also needs to be considered. In this case, it is assumed that 0.51 green tonnes of biomass (bark and wood shavings, assumed moisture content (MC) of 50%) are required for drying (similar to Uasuf (2010)). This would result in a total biomass transport of 2.65 tonne roundwood/tonne pellets. Overall truck transport emissions to transport fresh roundwood to the wood pellet production facility are 62.33 kg CO_2eq/tonne pellets.

Pelletizing

The wood pellet production facility includes the debarking, chipping, drying, grinding and pelletization of the fresh softwood delivered at the plant gate. The debarking and chipping of roundwood is considered to consume 48 kWh per tonne pellets (Sikkema *et al.*, 2010). During drying (heat is delivered by bark and wood shavings) the electricity consumption is assumed to be 39.67 kWh per tonne pellets (Uasuf, 2010). Other process steps like pelletizing, cooling and other miscellaneous electricity consumption account for 73.67 kWh per tonne pellets, 42.5 kWh per tonne pellets and 16.29 kWh per tonne pellets respectively. In the Southern United States, the emission factor for electricity is 729 g CO_2eq kWh^{-1}, including 6.5% transmission losses (EPA, 2007), resulting in a GHG emission profile of the pellet plant of 158.3 kg CO_2eq per tonne pellets.

International transport

Train. A train distance of 300 km is considered between pellet plant and international harbour, where large oceanic vessels can be loaded. This assumption is substantially lower compared to the 781, 750 and 900 km mentioned in the GHG analysis of Sikkema *et al.* (2010), Magelli *et al.* (2009) and Uasuf (2010), as this case study setting is different. Within, on average, a distance of 300 km, a large forest supply area is available, therefore, a distance of 300 km is sufficient. The emission factor of train transport as specified by Magelli *et al.* (2009)is used to determine the GHG emissions related to train transport, this results in a GHG emission of 9.08 kg CO_2 per tonne pellets.

Oceanic transport

After port handling, the wood pellets are transported to the European mainland by large bulk ocean carriers. A travel distance of 7200 km is considered for transport from the Southeast of the United States to the Netherlands. The greenhouse gas emissions of oceanic transport are 0.0107 g CO_2eq per tonne-km. Taken into account a loss of 2% during wood pellet handling in the import harbour, the GHG emissions for oceanic transport are 92.4 kg CO_2 per tonne pellets.

Cofiring of wood pellets in Dutch power plants

The consumption of wood pellets for the production of electricity in Dutch power plants is calculated as 499 g of wood pellets per kWh electricity, based on a wood pellets lower heating value of 17.6 MJ kg^{-1} and a power plant conversion efficiency of 41% (Sikkema *et al.*, 2010). When considering truck transport, pelletizing and international transport emissions, the overall GHG emissions for 100% wood pellet fired electricity is 161.78 g CO_2eq kWh^{-1}, excluding silvicultural emissions.

Overall this would imply that every tonne of carbon harvested [assuming dry softwood contains 50% carbon (ECN

2012)] would result in 1.56 tonne wood pellets and could produce 3.13 MWh electricity in Europe. With avoided emissions of 1081 kg CO_2eq MWh^{-1}, this would result in 3.38 kg CO_2 avoided, excluding supply chain emissions. For the carbon balances in section 4, a carbon replacement factor is determined. This factor represents the avoided carbon emissions per tonne of carbon harvested. In this case the carbon replacement factor is 0.923, resulting in 3.38 tonne avoided carbon dioxide emissions per tonne of harvested carbon.

Results

Productivity in Southern pine plantations

In the period between World War II and today, the productivity of Southern pine plantations has increased rapidly due to tree improvement programmes and silviculture management practices. Cooperation between governmental organizations, research and forest industry is considered to be the basis for this success (Fox *et al.*, 2004). Figure 2 below gives an indication of the contribution of different forest management practices to the potential yield, and the decrease in rotation length of pulpwood plantations between 1940 and today in Southern pine plantations.

The potential to increase softwood yields in the South-eastern United States have been studied at large by different researchers. This section will highlight some of the relevant publications. Stanturf *et al.* (2003) published a detailed overview of potential yields of softwoods, including estimations of individual contribution of silviculture practices, from a researcher's perspective. The increase in productivity of high-intensively managed plantation compared with natural stands was also estimated by Stanturf *et al.* (2003). Most prominent factors were site preparation (21%), tree improvement (20%), fertilization (18%) and competing vegetation management (16%). An often quoted publication on potential softwood yields is that of Borders *et al.* (2004); which give the results of different forest plots subjective to different management regimes. As described by Borders *et al.* (2004), annual fertilization and competing vegetation control resulted in more than 180 Mg ha^{-1} at age 15; more than double the reference area without fertilization and vegetation control. This would correspond to roughly 12 Mg ha^{-1} yr^{-1}, the upper level of the data presented in Fig. 2. Aggregated interview responses of forest practitioners, as presented by Kline & Coleman (2010), estimated achievable yield of today's established plantations between 8 and 10 Mg ha^{-1}-year. Research plots are established to determine the practical yield response of the different silvicultural practices as the soil quality is also of influence (Vance *et al.*, 2010). As a result of the increased forest management, the growth rate as well as the total stocking increased (Borders *et al.*, 2004). A recent literature review of forest biomass yields was performed by Vance *et al.* (2010). The potential yield increase is dependent on various elements: tree improvement, competing vegetation control, fertilization, site preparation before planting and tree planting to enable proper spacing. Pine seedlings have improved in recent decades by tree improvement programmes, traditionally focusing on seedling survival, increasing tree growth, disease resistance and wood quality (Vance *et al.*, 2010). Site preparation provides seedlings with a jump start over other vegetation on site. It can include chopping, windrowing, burning, ripping, bedding, fertilization and herbicide application (Wear & Greis 2002). After site preparation, pine seedlings can be planted mechanically or by hand. Fertilizer application in managed pine plantation during plant establishment (after thinning and midrotation) is becoming a common practice in the South (Wear & Greis 2002). Soil nutrient availability, especially nitrogen and phosphorus, is an important growth-limiting factor in Southern pine plantations (Jokela, 2004; Fox *et al.*, 2007). Control of competing vegetation is today mainly done by chemical treatment, thereby replacing prescribed burning to reduce competing vegetation in forest plots (Wear & Greis 2002). Vegetation control can also be performed mechanically; this can include: anchor chaining, chopping, burning, root raking, shearing and disking (Fox *et al.*, 2004).

The overall yield is set for the different scenarios based on the potential yield achievable under different forest management intensities. For the low-productive plantation, the overall yield after 25 years is 101 tonnes of dry biomass per hectare. A fertilized plantation, medium-productive plantation is assumed to yield in total (including midrotation thinning) 140 tonne dry biomass per hectare over a rotation period of 25 years. For the high-productive plantation the overall yield is 194 tonne

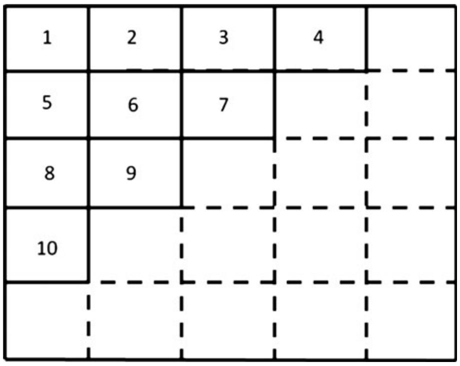

Fig 2 Increasing stand level approach, in this case after 10 harvests.

dry biomass per hectare, in this case the rotation period is only 20 years. High management intensity is unlikely given the low demand for softwood pulpwood size material and the higher feedstock costs if cultivated under more intensive management compared with lower management intensity. We estimated feedstock production costs as 3.5, 5.6 and 7.6 € per dry tonne (based on the above described scenarios), excluding land use or land ownership fee or taxes and excluding harvesting and hauling costs.

Greenhouse gas emissions in the supply chain

The GHG emissions of the wood pellet supply chain consist of the emissions during biomass cultivation, harvesting, transport and conversion of raw feedstock to wood pellets.

Silviculture emissions

In this section, the GHG emissions during cultivation of fast-growing softwood species are presented. Silviculture emissions include the fossil fuel consumption of (a) forest management equipment used during planting, fertilizer application, herbicide applications, thinning and harvesting, (b) fertilizer and herbicide production and (c) N_2O emissions from fertilizer application. The life-cycle emissions for seedling production are not taken into account due to data availability, but are likely to be small. The fossil fuel consumption of different silvicultural practices is given by (2009). The total life-cycle emissions from fertilizer production are taken from LCA databases, excluding emissions after application. The N_2O emissions related to fertilizer application are determined by the IPCC methodology. See Tables 1–3 for a detailed overview of low-, medium- and high-yield systems respectively. It includes the use of references and data concerning the carbon emissions of the different silvicultural practices under the low, medium and high management intensity scenarios respectively.

Table 1 Low-productive plantation carbon emissions and costs of silviculture practices, including harvesting emissions

Year	Activity	Fuel/chemical consumption	Carbon emission per hectare [kg C ha^{-1}]
0	Raking and spot piling	43 l fuel ha^{-1A}	39^{B}
0	Planting (1600 trees ha^{-1})^{D}	28 l fuel ha^{-1C}	26^{B}
25	Harvesting	616 l fuel ha^{-1E}	564^{B}
			6.23 kg C per tonne dry biomass

Important contributors to the carbon emissions during silvicultural practices are fertilizer production and applications, and diesel use during thinning and clear-cut harvest. Therefore, there is a large difference between the emission factors of the low management intensity scenario and the medium and high management intensity scenarios.

After the cultivation phase (in this case, the cultivation phase also includes harvesting), the next elements are truck transport, pelletizing, international transport and cofiring in European power plants. Silviculture emissions, expressed as GHG emissions per kWh electricity, are 15.10, 38.86 and 47.70 g CO_2eq per kWh electricity for a low-, medium- and high-productive plantation respectively. Those values are extracted from Tables 1–3 above and include the dry matter loss of 7%. See Table 4 for an overview of GHG emissions of the wood pellet supply chain.

The goal of this section is to show the development of overall carbon balance for the three management intensity scenarios whereas the two different conceptual approaches: the stand-level approach and the landscape-level approach. The results are presented as cumulative carbon balances over 75 years. The following graphs include the carbon debt, silviculture

Table 2 Medium-productive plantation carbon emissions and costs of silviculture practices, including harvesting emissions

Year	Activity	Fuel/chemical consumption	Carbon emission per hectare [kg C ha^{-1}]
0	Raking and spot piling	43 l fuel ha^{-1A}	39^{B}
0	Bedding	53 l fuel ha^{-1F}	49^{B}
0	Planting (1600 trees/ha^{D})	28 l fuel ha^{-1C}	26^{B}
3	Fertilization	224 kg DAP ha^{-1G}	43^{H}
3	Fertilizer application	9 l fuel ha^{-1J}	31^{J}
15	Thinning	616 l fuel ha^{-1E}	564^{B}
15	Fertilization	358 kg Urea ha^{-1G}	520^{I}
15	Fertilizer application	9 l fuel ha^{-1J}	31^{J}
	N_2O emission N-fertilizer		377^{K}
25	Clear-cut harvest	616 l fuel ha^{-1E}	564^{B}
			16.03 kg C per tonne dry biomass

Table 3 High management intensity plantation carbon emissions and costs of silviculture practices, including harvesting emissions

Year	Activity	Fuel/chemical consumption	Carbon emission per ha [kg Carbon per ha]
0	Raking and spot piling	43 l fuel ha^{-1}[*]	39[†]
0	Bedding	53 l fuel ha^{-1}[**]	49[†]
0	Herbicide	3.36 kg Velpar ULW ha^{-1}[†††]	34[‡‡‡]
0	Planting (1600 trees ha^{-1}[§])	28 l fuel ha^{-1}[§]	26[†]
0	Planting stock		
0	Herbicide	11.2 kg Glyphosate ha^{-1}[†††]	103[‡‡‡]
0	Fertilization	224 kg DAP ha^{-1}[§§§]	43[§§]
0	Fertilizer application	9 l fuel ha^{-1}[¶¶]	31[¶¶]
1	Herbicide	11.2 kg Glyphosate ha^{-1}[†††]	103[‡‡‡]
5	Fertilization	140 kg DAP ha^{-1}[§§§]	27[‡‡]
5	Fertilizer application	9 l fuel ha^{-1}[¶¶]	31[¶¶]
5	Fertilization	431 kg Urea ha^{-1}[§§§]	625[§§]
	N_2O emission N-fertilizer		418[***]
12	Thinning	616 l fuel ha^{-1}[¶]	564[†]
12	Fertilization	140 kg DAP ha^{-1}[§§§]	27[‡‡]
12	Fertilization	431 kg Urea ha^{-1}[§§§]	625[§§]
12	Fertilizer application	9 l fuel ha^{-1}[¶¶]	31[¶¶]
	N_2O emission N-fertilizer		418[***]
20	Clear-cut harvest	616 l fuel ha^{-1}[¶]	564[†] 19.38 kg C per tonne dry biomass

[*] Fuel consumption of Caterpillar 525, 188 hp, for raking and spot piling: 43 l ha^{-1} (Markewitz, 2006).

[†] GHG emission of diesel fuel: 0.916 kg Carbon per l fuel (Hoefnagels *et al.*, 2010).

[‡] Fuel consumption of Caterpillar 525, 188 hp, with tree planter: 28 l ha^{-1} (Markewitz, 2006).

[§] Planting density: 650 trees per acre, based on input data for life-cycle analysis.

[¶] Harvesting equipment fuel use: feller buncher, skidder and forwarder: 616 l ha^{-1} (Markewitz, 2006).

[**] Fuel consumption of Caterpillar 525, 188 hp, with bedding plough: 52 l ha^{-1} (Markewitz, 2006).

[††] Application rate diammonium phosphate and urea, based on input data for life-cycle analysis.

[‡‡] GHG emission DAP production based on phosphorus fertilizer production 710 g CO_2eq kg^{-1} (Hilst *et al.* 2012).

[§§] GHG emission urea production based on nitrogen production 5330 g CO_2 kg^{-1} (Hilst *et al.* 2012).

[¶¶] Fertilizer application by helicopter: 9 l fuel ha^{-1}: 31 kg Carbon ha^{-1} (Markewitz, 2006).

[***] Direct N_2O emission of nitrogen fertilizer application according to IPCC guidelines, chapter 11 (IPCC, 2006).

[†††] Herbicide application high-intensity plantation (Markewitz, 2006).

[‡‡‡] GHG emission herbicide production: 9.1 kg CO_2 kg^{-1} active ingredient, application emission 1.4 kg CO_2 ha^{-1} (St. Clair *et al.*, 2008).

[§§§] Fertilizer application high-intensity plantation (Markewitz, 2006).

emissions, supply chain emissions, tree and litter carbon and avoided fossil carbon emissions. Note that the emissions, carbon pools and avoided emissions are expressed as carbon equivalent and not as carbon dioxide (equivalent) which is commonly used in greenhouse gas calculations (1 tonne of carbon equals 3.67 tonnes of CO_2). As forest carbon pools are usually expressed as carbon pools, we used carbon equivalent as unit for the carbon balances.

Stand-level and increasing stand-level approach

In Fig. 3, for the single stand-level approach, the carbon debt and cumulative (fossil fuel) emissions in the supply chain are presented as negative carbon pools (due to those emissions the atmospheric carbon increases). The forestry carbon pools presented here (tree carbon and litter) and avoided fossil fuel emissions are shown as positive carbon pools. The red line represents the balance of positive and negative carbon pools; where the line is below 0, this implies that at this point in time the total cumulative carbon emissions are higher than the avoided emissions. When the line crosses zero, initial net emissions have been 'paid back' by the regrowth of the plantation.

Another approach to determine the carbon payback is an increasing stand-level approach, as shown in Fig. 4. As every year a plantation is harvested and used for wood pellet production, the carbon debt increases every year up to the point that a plantation is harvested a second time (after 25 years). As the tree carbon is only considered after the initial harvest, the total tree carbon pool is low in the first years, but sharply increases by year 25, due to both tree growth and an increasing forest plot. Emission of transport and pelletizing are directly linked to harvested biomass; therefore, the cumulative emissions of transport and pelletizing increase annually (due to annual harvest).

Carbon payback periods for low-productive plantations

The results of a carbon balance for a low-productive plantation are shown in Fig. 3a. In the first years (directly after the initial harvest), the avoided emission by fossil fuel substitution are lower than the carbon debt and fossil fuel emission in the supply chain. Due to tree (re) growth, with stable supply chain emissions, the carbon balance becomes positive after 11 years. Due to the high carbon replacement factor, a high fraction of harvested tree carbon turns into avoided fossil fuel carbon. As the carbon debt is constant, the carbon balance trend is increasing, with only minor relapse at harvesting.

Under the increasing stand-level approach, the carbon payback period of a low-productive scenario increases to 18 years, see Fig. 4a. This is due to the fact that every year (up to year 25) the carbon debt of 1 ha is added to the total carbon debt. Simultaneously, an amount of fossil fuel carbon is replaced, followed by the regrowth of a plantation. As the carbon uptake of a plantation after replanting is low, the carbon payback period is extended compared with the even-aged stand-level approach.

Table 4 GHG emissions of the wood pellet supply chain, expressed as CO_2 eq/tonne of wood pellets

	Gramme CO_2eq per tonne pellets		
Silvicultural practices	30.27[*]	77.88[†]	95.61[‡]
Truck transport	62.33		
Pelletizing[§]	160.47		
Train transport	9.08		
Oceanic transport	92.4		
	Gramme CO_2eq per kWh		
Avoided GHG emissions [¶]	1081		

*Low-productive plantation.

†Medium-productive plantation.

‡High-productive plantation.

§In the United States, the emission factor for electricity is 729 g CO_2eq per kWh (EPA, 2007).

¶The fossil-fuel reference scenario is a pulverized coal fired power plant, operating in the Netherlands at an conversion efficiency of 41%. As specified by Koornneef *et al.* (2008) the direct and indirect GHG emissions totalling 1081 g CO_2 eq per kWh. This is consistent with the fossil power reference as specified by Sikkema *et al.* (2010).

Carbon payback periods for medium-productive plantations

The carbon balances of a medium-productive plantation, using a stand-level and increasing stand-level approach, are shown in Figs 3b and 4b respectively. The carbon pools are similar in both graphs. For both scenarios the carbon debt is set to 63 tonne carbon per ha. Compared with the low-productive scenario, the GHG emissions of silviculture, expressed in carbon equivalent, increased sharply, see section 3.2. Despite that, the impact on the overall carbon balance is limited, as the increased yield more than compensates for the silvicultural emissions, see Fig. 3b. The carbon balance of the medium-productive scenario, using the stand-level approach, is positive after 7 years. Again an increasing trend was observed, following the trend of the softwood growth.

Using the increasing stand-level approach for the medium-productive plantation scenario the payback period increases to 13 years, see Fig. 4b. Also in this approach the increasing cumulative fossil fuel emissions

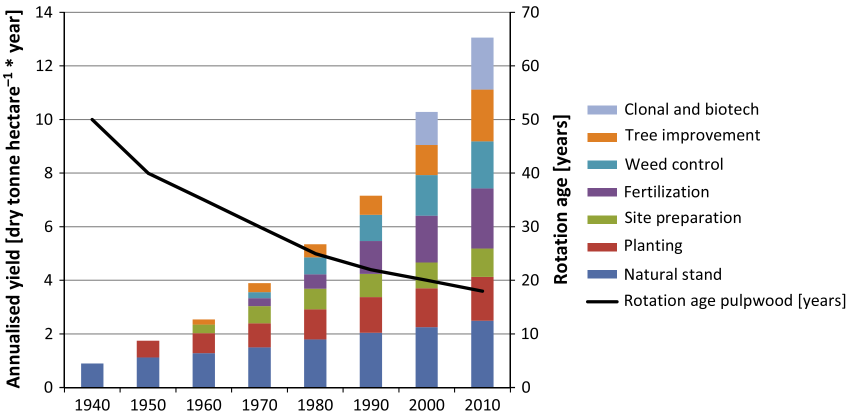

Fig 3 Estimated increase in upper limit yield, including indication of individual contribution, and rotation length in Southern pine plantations between 1940 and 2010, derived from Fox *et al.* [2004].

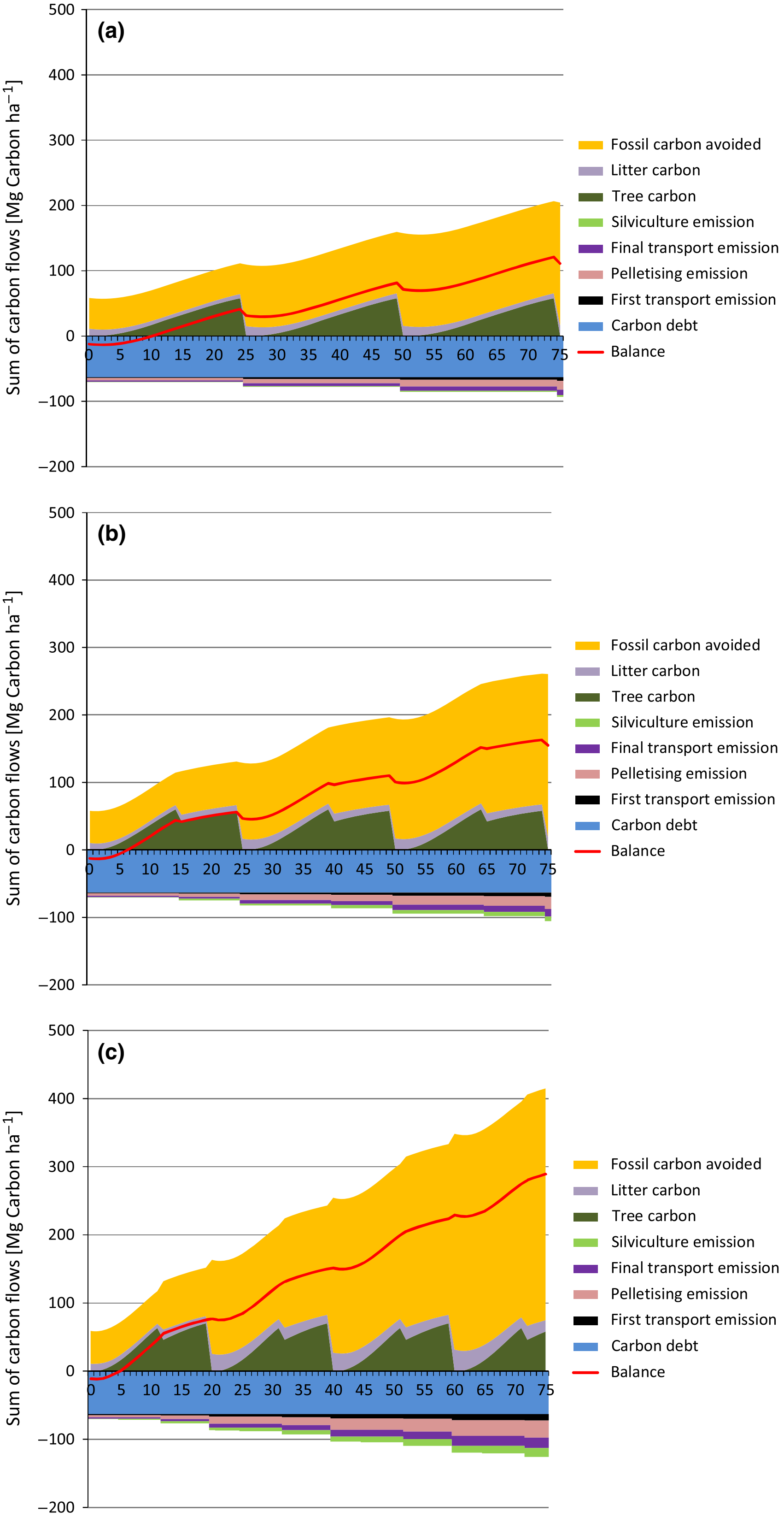

Fig 4 Carbon balance of 1 ha for a low- (a), medium- (b) and high (c) productive plantation, including emissions in supply chain and avoided coal emissions, utilizing a stand level approach.

in the supply chain are counteracted by the cumulative fossil fuel displacement for the improved yields.

Carbon payback periods for high-productive plantations

In Fig. 3c the carbon balance of a high-productive softwood plantation is shown. The high yield is a result of intensive forest management on high-quality seedlings, which increase silviculture emissions. Due to higher management intensity, the growth rate is higher compared with the low-productive scenario, the rotation period is therefore set to 20 years. The midrotation thinning is at age 12.

Using the stand-level approach, the carbon payback period is reduced to 5 years after the initial harvest. The carbon debt is repaid fast due to the high growth rate. As a result of this high growth rate the carbon balance trend is steeper compared with the low- and medium-productive plantations. The higher yield more than compensates for the higher emissions of silvicultural practices.

In Fig. 4c, the carbon balance of a high-productive scenario is shown using an increasing stand-level approach. Using this approach, the carbon balance of softwood plantations is positive after 12 years after initial harvest.

Carbon payback period for the landscape-level approach

A different approach to depict the carbon balance of softwood plantations is the use of a landscape-level approach, as discussed in the methodology section (section 2). In this analysis, the carbon balance with the landscape approach is depicted as the amount of carbon on 1 hectare. The landscape-level approach takes into account both the creation of a carbon debt, and at the same time the carbon uptake of the not-harvested area that year. In this way, the overall carbon stock of the area remains stable, as harvested carbon is less or equal to biomass (re) growth. The carbon balances of a low-, medium- and high-productive scenario are presented in Fig. 5a–c respectively. In the results, the carbon debt represents the average carbon debt of an uneven-aged plantations (ranging in the age from 0 to 25 years old). Every year, a carbon debt is created on a hectare, but this debt is basically directly compensated by the uptake on the 24 (or 19) other hectares within the plantation area. Due to this, the carbon payback period is reduced to less than 1 year; as in this case the carbon debt is similar to the carbon stock of the softwood plantation. When considering the landscape level all 25 ha are incorporated in the total supply chain. As in this analysis the forest growth equals the initial carbon debt, the carbon payback period is 1 year. In Fig. 5 the avoided carbon emissions of the different forest management intensity scenarios are clear; in the longer term the high-intensive scenario avoids the most fossil fuel carbon emissions.

Carbon offset parity point for productive scenarios

As shown in the previous section, when considering a landscape-level approach, carbon payback times become basically negligible (i.e. shorter than 1 year) even under the low-productive scenario. To determine a carbon offset parity point, the carbon balances (the purple line in Fig. 6) are compared with a 'no-harvest' scenario (the blue line in Fig. 6). In this scenario, the existing plantations are not harvested for wood pellet production or any other purpose. In this way, the softwood plantations could in theory serve as a carbon sink, a potential carbon mitigation strategy. Note, however, that after a certain amount of time, the uptake of carbon diminishes, and finally comes to halt as the plantation reaches an equilibrium state between growth and decay. Also, given the presence of the wood processing industry and upfront investments to enhance productivity in the South-eastern softwood plantations, not using softwood plantations on a large scale is considered unlikely, unless this method is seen as carbon mitigation strategy and land owners are (financially) reimbursed for not harvesting their trees.

In Fig. 7, the carbon balances of the three scenarios, expressed in the increasing stand-level approach, are compared with the carbon balance of nonharvested softwood plantation. For the three productive scenarios, only the overall carbon balances are shown. Next to those lines, the tree and litter carbon increase in an unharvested plantation is considered, this plantation differs in age between 0 and 24 years. Note that only the additional growth is shown; the base line is a 25-year-old softwood plantation. Not harvesting is favourable from a carbon balance point of view, until years 17, 22 and 39 for the high-, medium- and low-productive scenario respectively. In other words; the carbon offset parity point is at 17, 22 and 39, for the three scenarios. After the break-even point, use for wood pellet production is preferred over the nonharvest scenario from a greenhouse gas point of view. It is also clear that the absolute size of the temporary negative carbon balance is limited, whereas the positive carbon balance after break-even soon reaches levels many times greater. Using the increasing stand-level approach the carbon balance of the productive scenarios is more than double, triple or almost seven times greater compared with the 'no-harvest' scenario, after 75 years. Applying the landscape approach the difference is a factor 1.7, 2.3 or 3.8, for the low-productive, medium-productive

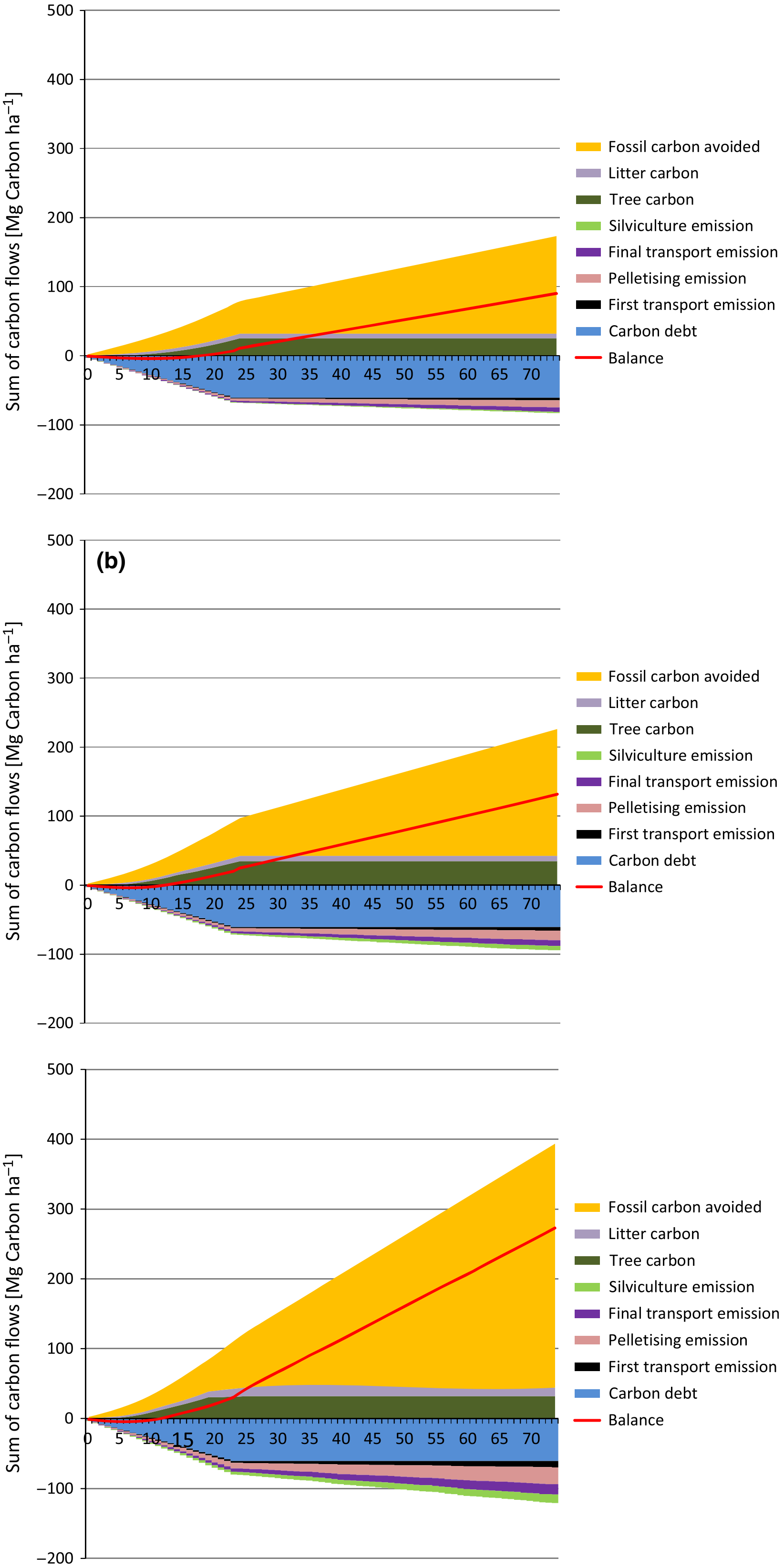

Fig 5 Carbon balance of 25 ha for a low- (a), medium- (b) and high (c) productive plantation, including emissions in supply chain and avoided coal emissions, using an increasing stand level approach.

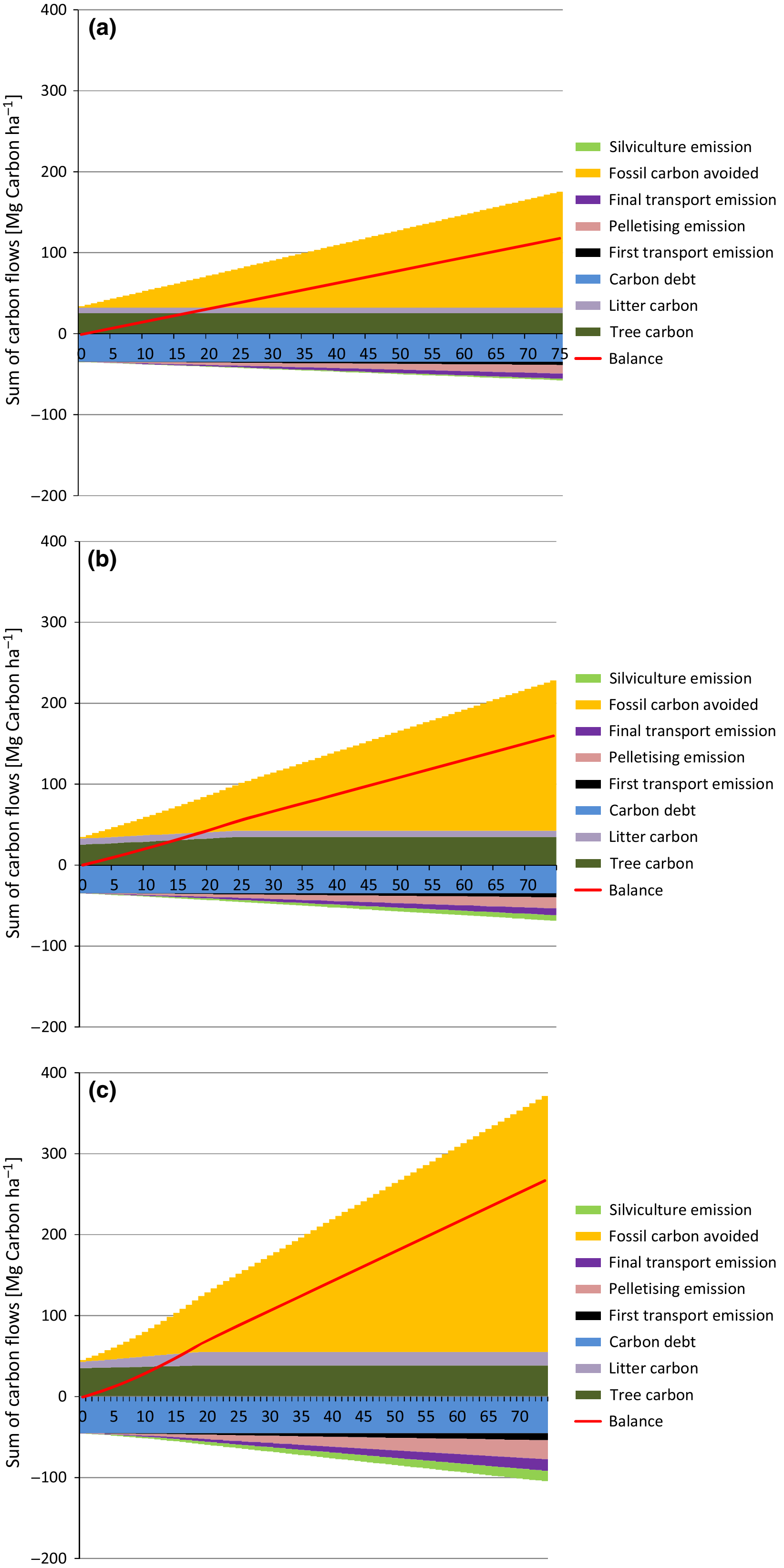

Fig 6 Carbon balance of 1 ha for a low- (a), medium- (b) and high (c) productive plantation, including emissions in supply chain and avoided coal emissions, using an landscape approach.

and high management intensity scenario, respectively, see Fig. 8.

Similarly, in Fig. 8, the carbon balances of the different scenarios are compared with a 'no-harvest scenario' using a landscape approach. The carbon parity point is at year 12, 27 and 46 for the high-, medium- and low-productive scenario, see Fig. 8. For the high-productive scenario the carbon offset parity point is shorter using the landscape-level approach compared with the increasing stand-level approach. On the other hand, the low-productive scenario results in higher carbon offset parity points when comparing the two approaches.

This can be explained by the typical S-shaped tree growth curve, especially presented in the curve for tree and litter carbon for the 'no-harvest scenario'. In this analysis a S-shape growth curve is considered for softwood growth, therefore, within the 'no-harvest scenario' the additional growth diminishes.

The carbon balances presented thus far have been calculated that the wood pellets are cofired in an average Dutch coal power plant (41% efficiency) and that electricity from coal is replaced. In Table 5, an overview is given for the carbon payback period (stand level) and the time until carbon parity point is reached (landscape

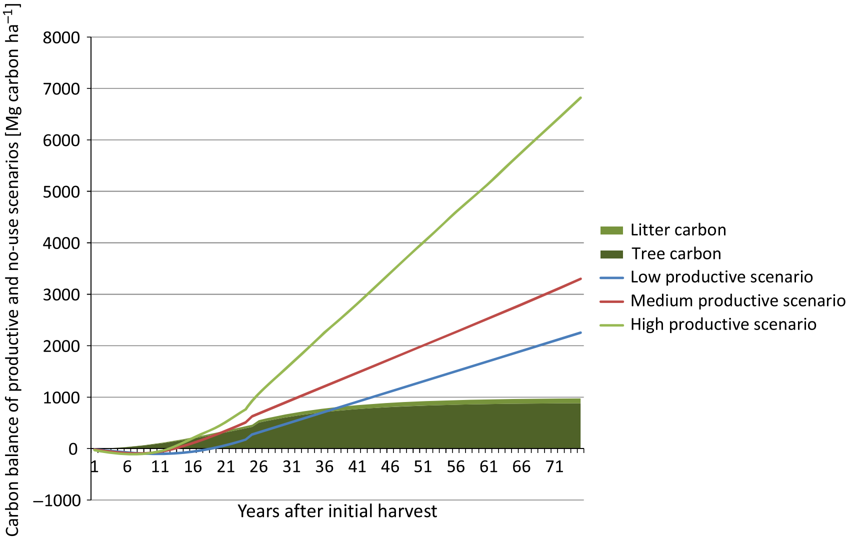

Fig 7 Carbon balances of productive scenarios compared with a no-harvest scenario, using an increasing stand-level approach.

Fig 8 Carbon balances of productive scenarios compared with a no-harvest scenario, using a landscape-level approach.

Table 5 Carbon payback time (stand-level approach) and carbon parity point (landscape-level approach) for the low/medium/high management intensity levels. The bold values are used in Figs 4–8

Electrical efficiency power plant	Fossil reference (gramme CO_2eq per kWh avoided emissions)	Carbon payback time in years (stand level)	Carbon parity point in years (landscape level) vs no harvest of existing plantations	Carbon parity point in years (landscape level) vs natural regrowth
35%[†]	713[¶]	27[*]/16[*]/8	106/68/39	91/59/15
	1081[**]	13/8/6	57/37/17	46/7/4
41%[‡]	713	22[*]/10/8	80/55/28	72/41/9
	1081	11/7/5	46/27/12	30/3/3
46%[§]	713	15/9/7	69/46/21	60/25/6
	1081	8/5/4	39/21/8	6/2/2

[*] The carbon balance of the low and medium management intensity crosses the baseline several times; the carbon payback here is defined as the total years the carbon balances are below zero.

[†] Coal plants older than 20 years typically have efficiencies of 35%, and are seen here as a worst case.

[‡] The electrical efficiency of an average Dutch coal fired power plant is taken from Koornneef *et al.* (2008).

[§] State-of-the-art coal power plants can reach 46% electrical conversion efficiencies, and are seen as a best case here.

[¶] The emissions profile of 713 g CO_2 eq per kWh is equivalent to the EU fossil fuel comparator of 198 g CO_2 per MJ electricity.

[**] See Table 4/(Koornneef *et al.*, 2008).

level) using also different electrical conversion efficiencies for the (coal) power plant in which the biomass is (co) combusted, and the emissions of the reference power plant. The absolute difference carbon balances of the productive scenarios and the no-harvest scenario are small, especially in the short term, see Figs 7–9. As a result of that a small difference in the case study input parameters could have a large effect on the carbon parity point. Or the carbon parity point is reached quickly or after the carbon balance of the reference scenario stabilizes.

Figure 9 shows the carbon parity point of the three productive scenarios compared with a 'natural regrowth' scenario. Such a scenario could occur when land owners do not expect any future markets for round wood (neither for material nor energy purposes), and thus abandon their plots after the current harvest. Under such circumstances, natural regrowth would occur, resulting in significantly slower carbon uptake compared even with low-management plantations. Under such an alternative reference scenario, carbon payback and parity times are shortened to 8–33 years.

Impact on GHG saving potential

In the previous section, we have illustrated various carbon balances over time. To actually quantify GHG savings, it is necessary to choose a time horizon, e.g. GHG savings within the next 20 years. The results of greenhouse gas accounting in biomass production can also be calculated according to this methodology, similar to the EU methodology for GHG accounting European Commission (2010).

The EU methodology takes into account the carbon stock change between the initial carbon stock and the carbon stock when the energy crop matures, with a maximum of 20 years after the initial harvest or conversion of land into plantation. This is depicted as the carbon stock change bar in Fig. 10. Note that in the case of switching from a low- to high-productive plantation, the carbon stock after 20 years is actually higher than in the initial state, resulting in a negative emission.

Next to the carbon stock change, the supply chain emissions are incorporated as well, identical to the other approaches described above. The overall emissions are compared with a general fossil fuel comparator (198 g CO_2eq per MJ electricity). In Fig. 10, the overall emissions of wood pellets are presented. The silviculture and supply chain emissions and carbon stock change emissions are expressed as carbon dioxide equivalent per MJ electricity. The supply chain emissions (truck, pelletizing, train and oceanic transport emissions) are identical for all scenarios. The carbon stock change is the difference between the carbon stock before initial harvest or land-use change, compared with the carbon stock of the land in use before biomass production. In this case the carbon stock of the actual land use is the carbon stock after 20 years, as forestry biomass accumulates over more than 1 year, and softwood trees reach maturity after more than 20 years. The carbon stock change is recalculated to CO_{2eq} emissions per MJ electricity, including the conversion of harvested tree carbon into wood pellets output, dry matter losses in the supply chain and power production efficiency. In our analysis the carbon stock change is defined as the difference between the carbon stock of a mature (25 years old) low-productive softwood plantation and the carbon stock after 20 years of initial harvest. This analysis shows that the carbon stock change is an important element of the overall GHG emission profile of wood pellet fired electricity. It could double the overall GHG emission footprint or reduce the emission profile to zero, see the net emission, represented by the red dots in Fig. 10. Seen from a GHG emission profile, determined according to the above described methodology, the high management intensity scenario is favourable over the medium- and low-productive scenario.

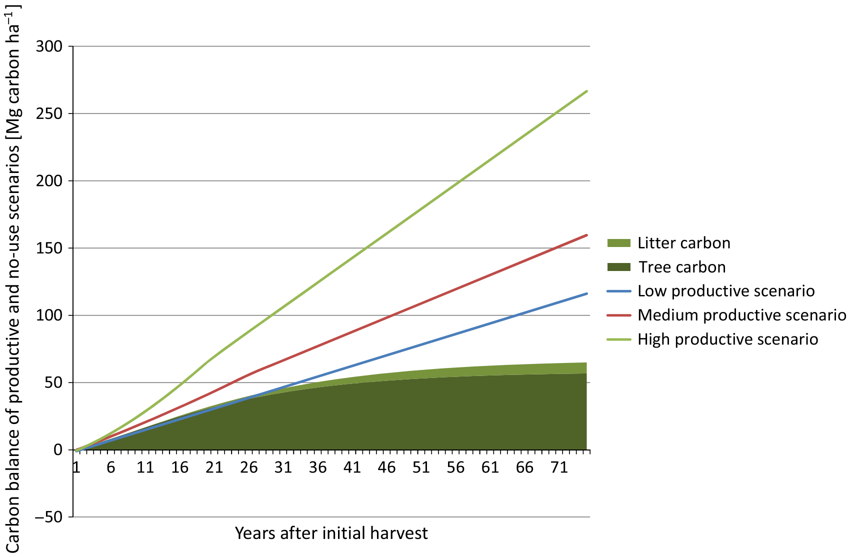

Fig 9 Carbon balances of productive scenarios compared with a natural regrowth scenario, using a landscape-level approach.

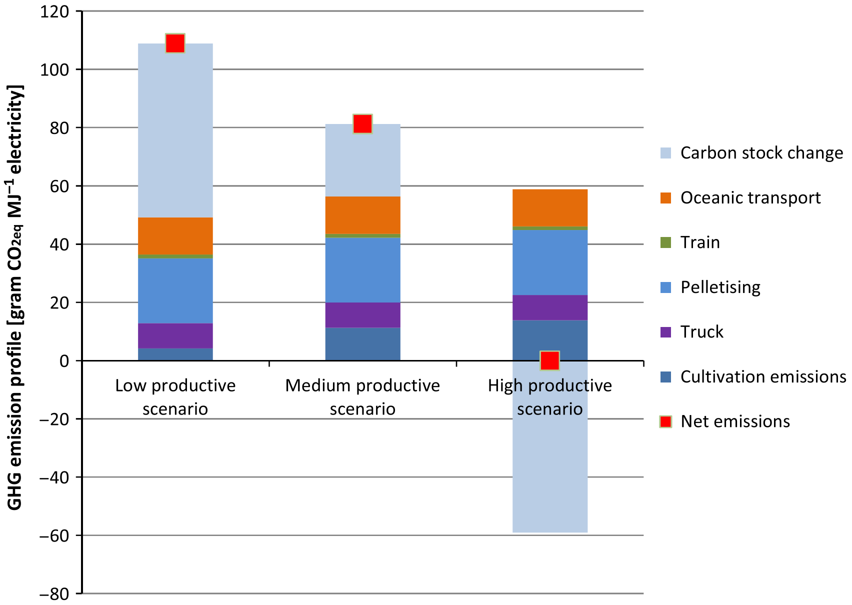

Fig 10 Average GHG gas emission profile of wood pellet fired electricity, expressed as CO$_{2eq}$/MJ electricity, for the low-, medium- and high-productive plantation scenario of the first harvest.

However, this result only applies for the first harvest, as subsequent harvests would not show any further carbon stock depletion if the harvesting frequency remains constant. Therefore, these results do not apply for second- or third-generation forest plantations.

Discussion

The result of the carbon balances clearly demonstrate that the choice of carbon accounting method has a significant impact on the carbon payback and carbon offset parity point calculations. When only looking at the carbon debt a landscape level, the time spans to reach break-even point become negligible, i.e. shorter than 1 year.

However, most other studies (Walker *et al.*, 2010; Zanchi *et al.*, 2010; Colnes *et al.*, 2012; Mitchell *et al.*, 2012) use the carbon offset parity point method. When comparing our results with these studies, we find that the carbon offset parity point is reached after 17, 22 and 39 years for the increasing stand-level approach. Applying the landscape approach, the carbon offset parity point is reached after 12, 27 and 46 years, for the high-, medium- and low-productive scenario. These times are shorter than the time spans identified by the studies cited above, which find carbon payback periods of <1 year for wood pellet production on former agricultural land (Zanchi *et al.*, 2010; Mitchell *et al.*, 2012), between 16 and 90 years on forested land (Walker *et al.*, 2010; McKechnie *et al.*, 2011) and 19 to 1000 years for old-growth forests (Zanchi *et al.*, 2010; Mitchell *et al.*, 2012). Both the methodology used and data input are of major importance. In our analysis, the data input is region specific; especially on the carbon stocks and growth curves of softwood plantations in the South-eastern United States softwood plantations. Next to this we identify the following reasons for the differences:

- The carbon debt considered is of a mature softwood plantation in a (subtropical) climate, as compared with old-growth (boreal) forests in equilibrium, which are used in other studies (Zanchi *et al.*, 2010; Mitchell *et al.*, 2012). In our case study, the growth rate of softwood is high compared with hardwood species or boreal (unmanaged) forests. Therefore, the carbon debt is repaid rapidly by the regrowth of the plantation.
- Some scenarios presented (e.g. Zanchi *et al.*, 2010; Mitchell *et al.*, 2012) assume significant soil carbon loss, when old-growth forests are converted into plantations. Typically, the pine plantations considered in our study were established decades ago. During harvest residues are left on site, thereby making the probability of soil carbon loss relatively low. Thus, we assume no soil carbon change, which is also in line with Colnes *et al.* (2012). We point out that no data on soil carbon changes under different management intensities were available. We agree with Skog & Stanturf (2010), who point out that more research is needed to identify forest types, and soil combinations were potential soil carbon loss could be triggered. In comparison, Zanchi *et al.* (2010) considered a high carbon debt, as in this scenario harvesting residues were removed.
- Total amounts of carbon stored in old-growth forests (as assumed, e.g. by Zanchi *et al.* (2010)) are typically much higher than in the pine plantations we use. For example, Zanchi *et al.* (2010) assume in a worst case scenario an initial carbon debt of 275 tonne C ha^{-1}. For comparison, such carbon levels are only found in our study area in mature swamps, including both soil and nonsoil. As such areas are also strictly protected, it is not possible to incur such high carbon debts in our study area. However, if (hypothetically) this would be possible, the carbon payback period in our case study would increase to 55–132 years for a stand-level approach, compared to 150–200 years found by Zanchi *et al.* (2010).
- The efficient supply chain and high fossil fuel carbon replacement is of large influence. The carbon replacement factor (or carbon efficiency) is high in this case study; 0.92 tonne of fossil fuel carbon is replaced by 1 tonne of harvested (biomass) carbon. Mitchell *et al.* (2012) used a carbon replacement factor of 0.51. This is due to the fact that he considers the avoided carbon emissions and supply chain emissions at the same time, assumes a rather low biomass conversion efficiency and assumes that biomass replaces a fossil fuel mix instead of solely replacing coal. As wood pellets directly replace coal in our case study, a 0.92 replacement factor seems justified.

Finally, we point out that in our case study, the choice of ‘no-harvest’ as reference scenario for the parity offset point calculations is not straightforward. From interviews with forest experts in South-eastern United States, we consider ‘no-harvest’ and ‘natural regrowth’ scenarios as not realistic; without financial compensation it is likely that plantations that are not harvested for timber/fibre would be converted into, for example, urban development or agricultural land. In such a case, no or significantly less carbon would be fixed in the reference scenario, which would then most likely be far worse than any bioenergy scenario.

Using the stand-level approach, the carbon payback period of a single stand varies between 5 and 11 years, dependent on the management intensity scenario. For the carbon offset parity point, using the increasing stand-level approach, the productive scenarios are preferred after 17–39 years. For the landscape approach, the range is even wider: from a 46 years carbon offset parity period in the worst case, to a mere 12 years for a high-intensity scenario. The input parameters are case study specific and methodology dependent; therefore, the results are case study specific as well, and can differ substantially between cases. We conclude that:

- Forest carbon accounting models are important for a better understanding of carbon stock change over time, essential parameters are (annualized) yields, carbon replacement factor and initial carbon stock (carbon stock change due to management or land-use change). The choice of methodological approach has a large impact on the calculations of carbon payback period or carbon offset parity point.
- When the ‘no-harvest’ scenario is compared with the bioenergy scenarios, we conclude that initially, the carbon balance of the ‘no-harvest’ scenario is

more favourable. However, after the carbon offset parity points (see above) the bioenergy scenarios are favourable. Therefore, apart from the question how realistic no-harvest or natural regrowth scenarios are (i.e. what the economic implications of such scenario would be), not utilizing softwood plantations for wood pellet production is not a viable pathway to structurally reduce GHG emissions on the longer term.

- This analysis points out that switching to highly productive plantations (only if sustainably managed) increases the uptake of carbon strongly, which offsets the additional emissions of silvicultural practices by far. Increased silvicultural emissions are compensated by faster (re) growth of plantations, and thereby increased uptake of carbon and increased fossil fuel displacement. However, given the low current softwood stumpage prices (a result of ample supply), it is expected that this scenario is not executed currently at large scale by land owners as silvicultural costs are higher for higher management intensities.
- The results show that the time before the carbon debt is repaid or time before the carbon offset parity point is reached strongly varies on (a) the management system and (b) the methodological choices. We consider the landscape-level carbon debt approach more appropriate for the situation in the South-eastern United States, where softwood plantation are already in existence, and under this precondition, we conclude that the issue of carbon payback is basically nonexistent. Assuming that coal is directly replaced in an average coal power plant, the carbon offset parity point (compared with no-harvest scenario), however, is in the range 12–46 years; i.e. one or two rotations. The absolute difference in avoided carbon emissions before the carbon offset parity point is relatively small in our case study, the benefits gained after the parity points is reached, however, are substantial.

Carbon balances of forestry biomass are case study specific (region and forest type), therefore we would suggest to utilize carbon accounting models to other locations, with its own specific characteristics. The data availability for soil carbon data is an issue; more research is needed on where soil carbon loss can be triggered.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Table S1. Input parameters for GORCAM carbon accounting model.