Title

Efficacy of Carbon and Bioenergy Markets in Mitigating Carbon Emissions on Reforested Lands: A Case Study from Southern United States

Author

Puneet Dwivedi¹, Madhu Khanna², Ajay Sharma³, Andres Susaeta⁴

¹ Warnell School of Forestry and Natural Resources, University of Georgia, Athens, GA

² Department of Agriculture and Consumer Economics, University of Illinois, Urbana, IL

³ Department of Agriculture and Environmental Science, Lincoln University, Jefferson City, MO

⁴ School of Forest Resources and Conservation, University of Florida, Gainesville, FL

Corresponding Author

Puneet Dwivedi, PhD

Assistant Professor (Sustainability Sciences)

Warnell School of Forestry and Natural Resources, University of Georgia

180 E Green Street Athens, GA (30602- 2152)

Phone: +1-706-542-2406 | Fax: +1-706-542-8356

Email: puneetdwivedi@gmail.com | puneetd@uga.edu

Abstract

Carbon markets would encourage forest landowners to increase rotation ages of their plantations. Emerging wood-based energy markets would increase prices of small-diameter timber products, thereby encouraging forest landowners to possibly opt for shorter rotation ages. We developed a comprehensive forest carbon model to track four carbon pools (carbon related to silvicultural activities, carbon sequestered on forestlands, carbon sequestered in wood products and wood present in landfills, and avoided carbon emissions) at the stand level to determine efficiency of carbon and bioenergy markets in mitigating carbon emissions with and without any change in rotation ages. Slash pine (*Pinus elliottii*) – a common species planted across the Coastal Plain of Georgia and Florida was taken as a representative species. We find that an increase in rotation age does not necessarily transform into additional carbon savings relative to some base rotation ages over a planning horizon of 100 years. Similarly, a decrease in the rotation age is not necessarily beneficial from carbon perspective either with respect to some base rotation ages. The utilization of all timber products for manufacturing of wood pellets to generate electricity in the United Kingdom maximizes carbon savings without any change in the rotation age. Suitable safeguards need to be incorporated in existing forest and bioenergy certification schemes to ensure efficacy of reforested lands in mitigating carbon emissions. Climate policies should emphasize on a systemic approach to maintain carbon mitigation potential of the forestry sector over time.

Keywords

Carbon Market, Wood-based Bioenergy Development, Carbon Sequestration, Avoided Carbon Emissions, Forest Management, Rotation Ages, Southern United States.

Introduction

About 28 million metric tons of forest carbon credits (carbon dioxide equivalent) worth US \$ 216 million were traded in 2012 globally out of which about 30% were traded in North American only (Forest Trends, 2013). It is quite likely that forest carbon markets will expand further as several multinational corporations, governmental agencies, and non-governmental organizations are interested in buying forest carbon credits to offset their greenhouse gas (GHG) emissions. Existing studies suggest that forest carbon markets would encourage forest landowners to increase rotation age of their plantations as additional carbon sequestered on their forestlands will provide monetary benefits to them (Dwivedi et al., 2012b; Gutrich and Howarth, 2007; Sohngen and Brown, 2008; van Kooten et al., 1995).

At the same time, manufacturing of wood pellets is rapidly expanding in the United States mostly to meet demand from European countries where wood pellets are increasingly being used as a feedstock for electricity generation. In fact, the United States has become the largest exporter of wood pellets in the world primarily to the European Union (Ekstrom, 2012). It is projected that the exports of wood pellets would reach to about 6.0 million metric tons by 2016 (Lang, 2014) totaling US \$ 1000 million at current market rates. Existing studies suggest that the demand for wood pellets will increase prices of small-diameter wood products in domestic markets (Abt et al., 2012, 2010; Guo et al., 2011). This increase in prices could encourage forest landowners to decrease the rotation age of their plantations as availability of small-diameter wood products, especially pulpwood is high for early plantation ages (Yin et al., 1998).

No study, to the best of our knowledge, has analyzed the consequence of a change in the rotation age on total carbon savings over time by considering all the major forest carbon pools (carbon related to silvicultural activities, carbon sequestered on forestlands, carbon sequestered in wood products and wood present in landfills, and avoided carbon emissions) together at the stand level using common system boundaries and under similar set of assumptions for reforested lands.

The majority of existing studies focusing on the role of emerging carbon markets on the forestry sector have focused on the impact of carbon prices on the profitability of forest landowners at the stand level (Dwivedi et al., 2009; Stainback and Alavalapati, 2002), quantifying changes in timber markets (Alig and Butler, 2004; Sohngen and Sedjo, 2000), and projecting land use changes (Lubowski et al., 2006). Similarly, the majority of studies focusing on emerging markets for wood-based energy products have focused on the carbon intensity of wood-based energy products (Damen and Faaij, 2006; Dwivedi et al., 2012a, 2011), stand-level economics (Susaeta et al., 2009), market equilibrium (Abt et al., 2012; Daigneault et al., 2012), and direct-indirect land use changes (Daigneault et al., 2012; Searchinger et al., 2008; Wang et al., 2015). This missing information is critical from a climate policy perspective to strengthen the role of forestry as an effective tool for carbon mitigation (Woodbury et al., 2007) especially when forestry is considered as a low cost carbon mitigation option (McCarl and Schneider, 2001; Richards and Stokes, 2004).

Methods

This study analyzed four different scenarios (Table 1). A total of 82 different cases ((two forest management choices (intensive and non-intensive) and 41 rotation ages (10 to 50 years in annual

steps)) were analyzed under each scenario when the original rotation age did not change over a 100 year planning horizon. However, a total of 3280 different cases ((two forest management choices (intensive and non-intensive), 41 original rotation ages (10 to 50 years in annual steps), and 40 new rotation ages (10 to 50 years in annual steps excluding the original rotation age)) were analyzed under each scenario when the original rotation age did change at the onset of planning horizon of 100 years. We tracked trajectory of all selected carbon pools for all the cases present under each scenario (Figure S1).

Under intensive forest management, herbicides (at plantation establishment year) and fertilizers (at 2nd and 12th year of plantation) were applied (Yin et al., 1998). These inputs were not used under non-intensive forest management (Yin et al., 1998). For each scenario, four carbon pools were considered: carbon sequestered in above- (live timber products, dead trees, foliage, forest floor, and understory vegetation) and below-ground biomass (coarse roots); carbon emissions from silvicultural practices; carbon sequestered in wood products and wood present in landfills; and avoided carbon emissions due to the substitution of grid electricity with the electricity generated using wood pellets in the United Kingdom¹. This study focuses on the southern United States as this region supplied about 62% of total roundwood in 2006 at the national level (Smith et al., 2009). This region is also a major exporter of wood pellets to the European countries supplying about 98% of all exported wood pellets (Ekstrom, 2012). Slash pine (*Pinus elliottii*) was selected as a representative species due to its popularity among forest landowners in the Coastal Plain of Georgia and Florida (Smith et al., 2009).

¹ About 73% of total exported wood pellets from the United States are consumed in the United Kingdom (USEIA, 2015).

A growth and yield model of slash pine was used to estimate availability of three timber products (sawtimber, chip-n-saw, and pulpwood) from a hectare of slash pine plantation for intensive and non-intensive forest management choices (Yin et al., 1998). Intensive and non-intensive forest management choices were selected to reflect active and passive forest landowners, respectively. The availability of logging residues at any harvest age was calculated as the difference between total biomass present in stems and total biomass present in merchantable portion of stems (sawtimber, chip-n-saw, and pulpwood) at the stand level plus 12% of all biomass present in merchantable portion of stems at a given rotation age (Alabama Forestry Commission, 2015). Additional 12% biomass was added as a proxy for biomass available in branches and tree tops. Total carbon sequestered in other above- and belowground pools was equal to the product of total carbon sequestered in timber products and an allocation ratio. The allocation ratio was 35% at the 10th year of plantation, 27% for plantation ages 11 to 20 years, 26% for plantation ages 21 to 30 years, and 25% for plantation ages 31 years and above (Gholz and Fisher, 1982; Gonzalez-Benecke et al., 2010). At any rotation age, quantity of carbon sequestered in timber products was added to carbon sequestered in other above- and below-ground pools to ascertain total carbon sequestered on a hectare of slash pine plantation. GHG emissions related to silvicultural activities were allocated to available timber products by the percentage weight contributed by each timber product towards their combined weight at any plantation age (Table S1).

This study assumes that a forest landowner will either maintain the original rotation age over the planning horizon or opt for a new rotation age (higher or lower) at the end of original rotation age and the beginning of the planning horizon (Figure 1). Under the situation when a forest landowner maintains the original rotation age, the quantities of carbon sequestered in wood

products and wood present in landfills² and avoided carbon emissions at the end of the planning horizon were added together to determine total carbon savings (Equation 1). We have not considered total carbon sequestered in above- and belowground carbon pool to calculate total carbon savings when there is no change in the rotation age as net sequestered carbon does not change in this carbon pool over time.

Equation 1

$$\text{Total Carbon Savings at the 100}^{\text{th}} \text{ year of Planning Horizon} = \text{Total Carbon Sequestered in Wood Products and Wood Present in Landfills at the 100}^{\text{th}} \text{ year of Planning Horizon} + \text{Total Avoided Carbon Savings at the 100}^{\text{th}} \text{ year of Planning Horizon.}$$

In the situation where a forest landowner opts for a new rotation age, quantities of carbon sequestered in wood products and wood present in landfills and avoided carbon emissions were added together for the original rotation age and then subtracted from the sum of the quantities of carbon sequestered in wood products and wood present in landfills and avoided carbon emissions for the new rotation age to determine partial net total carbon savings at the end of planning horizon (Equation 2). Net change in carbon sequestered in above- and below-ground carbon pool between the original rotation age and a new rotation age was added to partial net total carbon savings to determine net total carbon savings (Equation 3). We have considered only net change in carbon sequestered in above- and belowground biomass over the planning horizon between any two rotation ages to determine total carbon savings as the same forestland is being used for growing slash pine over time.

² The carbon sequestered in leftover logging residues was also added to this carbon pool for all scenarios.

Equation 2

Partial Net Total Carbon Savings at the 100th year of Planning Horizon = [Total Carbon Sequestered in Wood Products and Wood Present in Landfills at the 100th year of Planning Horizon for the New Rotation Age - Total Carbon Sequestered in Wood Products and Wood Present in Landfills at the 100th year of Planning Horizon for the Original Rotation Age] + [Total Avoided Carbon Savings at the 100th year of Planning Horizon for the New Rotation Age - Total Avoided Carbon Savings at the 100th year of Planning Horizon for the Original Rotation Age].

Equation 3

Net Total Carbon Savings at the 100th year of Planning Horizon = Partial Net Total Carbon Savings at the 100th year of Planning Horizon + [Carbon Sequestered in Above- and Belowground Carbon Pool for the New Rotation Age - Carbon Sequestered in Above- and Below-ground Carbon Pool for the Original Rotation Age].

This study followed Dwivedi et al. (2014) to ascertain quantities of carbon sequestered in wood products and wood present in landfills over the planning horizon and rotation ages. We adopted exponential decay functions for ascertaining decay of carbon sequestered in leftover logging residues and wood products (USEIA, 2011). Updated parameters used for determining quantities of carbon sequestered in wood products and wood present in landfills are in Table 2. Method of moving average was used to determine quantities of carbon sequestered in wood products and wood present in landfills at the end of planning horizon for each rotation age. We followed Dwivedi et al. (2014) to estimate avoided carbon savings due to the use of manufactured wood

pellets for electricity generation in the United Kingdom instead of coal. This study assumed that manufactured wood pellets were used to generate electricity at a 100 MW power plant in the United Kingdom. All updated parameters used for ascertaining avoided carbon savings are reported in Table 3. Avoided carbon savings at a given rotation age were divided by the corresponding rotation age itself to estimate average annual quantities. The obtained value was then multiplied by 100 to estimate cumulative avoided carbon savings the end of planning horizon in the United Kingdom.

Results

The availability of pulpwood was higher at initial plantation ages whereas the availability of large-diameter timber products (chip-n-saw and sawtimber) increased with a rise in the plantation age as trees gained girth and height with time (Figure 2). The availability of logging residues also increased with a rise in the plantation age reaching to a maximum value of 51.1 and 43.8 Mg ha⁻¹ under intensive and non-intensive forest management, respectively. Availability of pulpwood was higher than logging residues under intensive and non-intensive forest management choices for all plantation ages. The availability of logging residues was always higher under intensive than non-intensive forest management; however, the availability of pulpwood was higher under non-intensive than intensive forest management for plantation ages greater than 15 years. The combined availability of logging residues and pulpwood was higher under intensive than non-intensive forest management at all rotation ages, although the difference decreased from 65.2 Mg ha⁻¹ for the plantation age equal to 10 years to 1.1 Mg ha⁻¹ for plantation age equal to 50 years. Average annual availability of all timber products increased and

then decreased with a rise in the plantation age at different rates depending upon the availability of timber products at a given plantation age (Figure 3).

The sum of all timber products was higher under intensive than non-intensive forest management choice with the difference ranging from 122.7 Mg ha⁻¹ at the plantation age of 18 years to 30.7 Mg ha⁻¹ at the plantation age of 50 years (Figure S2). The average annual availability of total timber products increased with a rise in the rotation age and then started to decrease with a further rise in the rotation age. Carbon sequestered in above- and belowground carbon pools on intensive than non-intensive forest management choice was higher with the difference ranging from 38.6 to 0.03 Mg C ha⁻¹ for plantation ages of 27 and 10 years, respectively (Figure S3). Carbon sequestered in live timber products was about 79% of total carbon sequestered on the forestland across rotation ages.

Total carbon sequestered in wood products and wood present in landfills showed a cyclical trend with a period that matched the rotation age for intensive (Figure S4) and non-intensive (Figure S5) forest management. The trajectory of carbon sequestered in wood products and wood present in landfills was similar to other studies (Gonzalez-Benecke et al., 2010; Markewitz, 2006). Total avoided carbon savings due to the use of manufactured wood pellets for electricity generation in the United Kingdom increased linearly for both intensive (Figure S6) and non-intensive (Figure S7) forest management choices with respect to planning horizon. This linear trajectory is attributed to the fact that we annualized total avoided carbon savings to estimate exact quantities of avoided carbon savings at the end of planning horizon for each rotation age. Trajectories of carbon sequestered in wood products and wood present in landfills and avoided carbon savings

differed for each rotation age due to differences in the availability of timber products at each rotation age.

All scenarios led to carbon savings when a forest landowner did not change the original rotation age over the planning horizon (Figure 4). Carbon savings were typically higher under intensive than non-intensive forest management for corresponding scenarios due to the higher availability of timber products under intensive than non-intensive forest management. This clearly indicates that use of fertilizers helps in saving more carbon emissions over time on per unit land basis even after accounting for carbon emissions related to production and application of fertilizers. The optimal rotation ages at which total carbon savings were highest under scenarios LEFT-LR, ENE-LR, ENE-LR+PW, and ENE-ALL for intensive forest management were 21, 20, 12, and 17 years, respectively. Similarly, the optimal rotation ages at which total carbon savings were highest under scenarios LEFT-LR, ENE-LR, ENE-LR+PW, and ENE-ALL for non-intensive forest management were 27, 27, 16, and 23 years, respectively.

Carbon sequestered in wood products and wood present in landfills at the end of planning horizon decreased with an increase in the rotation age. This was mostly due to the fact that an increase in rotation age gives more time to the carbon already present in the wood products and landfills for decay. After a particular rotation age, the net decay of carbon present in wood products and landfills between two harvest cycles becomes greater than the net carbon input between the same harvest cycles. As a result, total carbon sequestered in wood products and wood present in landfills starts to decrease with an increase in the rotation age. Therefore, it is

not necessary that an increase in rotation age will always increase total carbon savings over time especially in carbon sequestered in wood products and wood present in landfills.

The availability of large-diameter wood products played a critical role for carbon sequestered in wood products and wood present in landfills as carbon sequestered under the case LEFT-LR was only slightly higher than the carbon sequestered under the cases ENE-LR and ENE-LR+PW at the end of the planning horizon. Carbon savings were highest for the case ENE-ALL followed by cases ENE-LR+PW, ENE-LR, and LEFT-LR indicating that the utilization of all timber products for manufacturing of wood pellets and subsequent utilization of manufactured wood pellets for electricity generation in the United Kingdom could be the best alternative for increasing total carbon savings over time on reforested lands. Use of large-diameter timber products for manufacturing wood pellets may be economically prohibitive, but it does have significant implications for total carbon savings as a consequence of whole-tree harvesting for bioenergy development.

The magnitude of additional carbon saved varied considerably across scenarios and was dependent on the new rotation age relative to the original rotation age of 15 years (Figure 5). For example, under the scenario ENE-LR+PW, no additional carbon savings occurred when a forest landowner switched to a new rotation age of greater than 41 years as loss of carbon sequestered in wood products and wood present in landfills combined with the loss of potential avoided carbon savings became greater than any additional gain in carbon sequestered on forestland. Similarly, no additional carbon savings occurred under the scenario ENE-ALL when a forest landowner switched to a rotation age of greater than 42 years as any additional gain in carbon

sequestered on forestland became smaller than the combined loss of avoided carbon savings and carbon sequestered in wood products and wood present in landfills. No additional carbon was saved when a forest landowner opted for a reduced rotation age relative to the original rotation age of 15 years under all scenarios.

An increase in rotation age from the original rotation age of 30 years did not save any additional carbon under scenarios ENE-LR+PW and ENE-ALL at any rotation age greater than 30 years (Figure 5). Some additional carbon was saved under the scenarios LEFT-LR and ENE-LR when the new rotation ages were between 31-35 years and 32-34 years, respectively. Otherwise, no additional carbon was saved with respect to the original rotation age of 30 years at the end of planning horizon. A decrease in rotation age instead saved some additional carbon for cases ENE-LR+PW and ENE-ALL. When original rotation age was 45 years, additional carbon was saved in all cases where new rotation ages were smaller than 45 years.

The range of new rotation ages where additional carbon was saved with respect to the original rotation age was wide for smaller original rotation ages (Table 4). These new rotation ages were greater than the original rotation age as well. However, with a rise in the original rotation age, this range started to decrease. After a particular original rotation age, this range started to increase again but this time new rotation ages at which additional carbon was saved with respect to the original rotation age were smaller than the original rotation age. No additional carbon was saved at any new rotation age for cases LEFT-LR, ENE-LR, ENE-LR+PW, and ENE-ALL when the original rotation ages were 33, 33, 27, and 26, respectively under intensive forest management. Similarly, no additional carbon was saved at any new rotation age for cases LEFT-

LR, ENE-LR, ENE-LR+PW, and ENE-ALL when the original rotation ages were 41, 40, 33, and 33 years, respectively under non-intensive forest management.

Discussions

In the absence of any changes in rotation ages over the planning horizon, the use of wood pellets obtained from logging residues and then used for electricity generation increased total carbon savings especially with respect to the case when logging residues were left unutilized. We found that with respect to other cases, total carbon savings were much higher when all timber products obtained at a given rotation age were used for manufacturing wood pellets which were then subsequently utilized for generating electricity in the United Kingdom. For cases when only logging residues or both pulpwood and logging residues were utilized for manufacturing wood pellets, total carbon savings were higher relative to the case where pulpwood was used for paper making and logging residues were left on the ground.

Our results suggest that an increase in rotation age due to forest carbon markets may or may not save any additional carbon with respect to the original rotation age on reforested lands. As a result, a caution should be exercised while promoting forest carbon markets especially on reforested lands as additional carbon savings are very sensitive to new rotation ages with respect to current rotation ages typically practiced by forest landowners for slash pine in the southern United States. Similarly, a precautionary approach should be adopted for utilizing wood-based energy products as additional carbon saving are very sensitive to new rotation ages with respect to current rotation ages. It should be kept in mind that the chances that a forest landowner will change the existing rotation age to a shorter rotation age are very minimum as profitability of a

forest landowner is highest when a mixture of traditional timber products are produced along with pulpwood under current market conditions (Munsell and Fox, 2010). However, still a caution should be exercised while sourcing biomass for bioenergy development for ensuring long term sustainability of fast growing bioenergy markets in the southern United States.

A few studies have deliberated on the issue of carbon benefits of wood-based energy products. Some studies report immediate savings in GHG emissions (Dwivedi et al., 2012a, 2011) where as some studies state otherwise (Greene and Lyutse, 2011; Walker et al., 2012). Studies reporting immediate carbon savings typically do not consider a change in the rotation age whereas other studies do consider a change in rotation ages. Studies which emphasize that actual carbon savings from wood-based energy products will actualize over a very long time implicitly assume that increasing rotation ages with respect to standard rotation ages is inherently beneficial from carbon perspective. Our study clearly states that this assumption is not necessarily true especially when all major carbon pools are considered simultaneously over time.

Current carbon accounting guidelines do not explicitly account for changes in rotation ages on long term basis especially on reforested lands (Lal et al., 2011; Lim et al., 1999; van Dam et al., 2008). These guidelines mostly focus on forest management practices and direct-indirect land use changes (Searchinger et al., 2008). It is important to consider a change in the rotation age together with the existing indices to ensure carbon savings. A novel market-based mechanism for carbon payments will also be needed to ensure any changes in rotation ages are beneficial from carbon perspective. A blanket increase or decrease in rotation ages on reforested lands without any change in forest management practices might not save any carbon at the stand level over a

planning horizon as shown in this study. At the same time, it is necessary to identify suitable changes in forest management practices to ensure additional carbon savings with respect to the original rotation age, as continuing similar forest management practices with changed rotation ages might not save any additional carbon either. We also emphasize on taking a systemic approach for ensuring forestry as a tool of carbon mitigation. A short sighted approach could increase carbon emissions from existing forestlands than reducing them overtime.

Our study is most relevant to slash pine under the assumed set of silvicultural practices. The approach adopted in this study should be replicated with other commercial species to ascertain relevancy of our findings across a range of species. This is especially true as a large variation exists among different species in terms of their growth rates, availability of timber products, utilization pattern of obtained timber products, and rotation ages. There also exists a need to develop a similar but broader modeling framework to incorporate more silvicultural practices opted by forest landowners for the range of commercial wood species in the United States e.g., use of thinned material either for paper making or manufacturing of wood pellets for export purposes. Additionally, the modeling framework developed in this study should be explicitly used as an input to regional (Abt et al., 2012), national (Alig et al., 2010), or global (Buongiorno et al., 2003) timber market models to ascertain potential of carbon savings at various scales. This is particularly true as a recent study by Wang et al. (2015) clearly indicates that a rise in demand of wood pellets for exports will bring an additional 1.4 million hectares of land into forestry but decrease the average harvest age over time. It was found that an increase in afforestation compensates any losses related with a change in rotation ages. However, this study has not analyzed the combined effect of carbon and bioenergy markets on direct and indirect land use

changes and any changes on optimal rotation ages – a critical gap in our understanding considering both these markets are operating at the same spatial and temporal scales.

We have not considered carbon sequestered in soil horizons and carbon emissions related to the decay of post-harvested sub-soil organic matter due to lack of sufficient data and uncertainty (Currie et al., 2003; Johnson and Curtis, 2001; Nave et al., 2010) especially for the selected cases. It is our assertion that the overall results of this study will not change even after including these two carbon pools as the majority of carbon sequestered in deep soils on reforested lands remains constant and emissions from labile carbon pools are fully recovered in initial few years of plantation growth (Bracho et al., 2011; Davis et al., 2012; Johnson, 1992). Additionally, some studies doubt the sustainability of productivity of intensively managed plantations over long time because frequent removal of biomass, including logging residues, not only promotes depletion of soil nutrients but also leads to deterioration of the physical and chemical properties of soil (Tiarks, 1990). This study, however, does not account for such possible deteriorations in feedstock availability. We hope that future studies will deliberate on these issues and advance our understanding about the role of forestry as a tool of carbon mitigation.

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Figure 1: Assumptions about the rotation ages. At the onset of the planning horizon, a forest landowner can continue with the original rotation age (20 years) or can opt for a new rotation age (15 years or 30 years). Same is true for other rotation ages analyzed in the study.

Figure 2: Availability of timber products at a given plantation age. Site index of plantation was 21.3 m at 25th year of plantation with an initial plantation density of 1235 seedlings ha⁻¹.

Figure 3: Average annual availability of timber products at a given plantation age. Values in Figure 3 are obtained by dividing the values in Figure 2 by the respective plantation age itself.

Figure 4: Total carbon savings without any change in the rotation age at the end of planning horizon. Top portion shows total carbon savings whereas bottom portion shows breakup of total carbon savings. Carbon sequestered in logging residues on the forestland is part of carbon sequestered in wood products and wood present in landfill for all the scenarios. Negative values show carbon savings.

Figure 5: Additional carbon savings with a change in the rotation age for intensive forest management at the end of planning horizon with respect to an original rotation age. Corresponding results for non-intensive forest management are in Figure S8. Negative and positive values show carbon savings and emissions, respectively.

List of Tables

Table 1: Scenarios analyzed in the study. Scenario LEFT-LR assumes that a forest landowner is leaving logging residues in the field and all other timber products are being used for traditional purposes. Scenarios ENE-LR and ENE-LR+PW are considered as emerging pellet market is using pulpwood as a feedstock. Scenario ENE-ALL represents whole-tree harvesting for pellet production as envisioned by several non-government organizations for existing state of wood pellet production in the southern United States. A schematic of Scenario ENE-LR is present in Figure S1.

Scenarios	sawtimber	chip-n-saw	pulpwood	logging residues
LEFT-LR	Lumber	Lumber	Paper	Left on the ground
ENE-LR	Lumber	Lumber	Paper	Wood pellets*
ENE-LR+PW	Lumber	Lumber	Wood pellets	Wood pellets*
ENE-ALL	Wood pellets	Wood pellets	Wood pellets	Wood pellets*

* Only 30% of available logging residues are used for wood pellets and remaining 70% are left on the ground only.

Table 2: Parameters for ascertaining carbon sequestered in wood products and wood present in landfills. Parameters reported in terms of GHG emissions were converted to their carbon equivalent by multiplying them with 12/44.

General assumption
Carbon present in harvested timber products (%): 25
Parameters used for plantation management
GHG emissions with intensive forest management before age 12 (Mg CO ₂ e ha ⁻¹): 2.9 GHG emissions with intensive forest management after age 12 (Mg CO ₂ e ha ⁻¹): 6.7 GHG emissions with non-intensive forest management (Mg CO ₂ e ha ⁻¹): 2.4 Half-life of logging residues (years): 5.7 (Mobley et al., 2012)
Parameters used for converting timber products into wood products
Moisture content of green wood on dry basis (%): 110 Bark present in green wood (%): 10 Lumber production from sawtimber (%): 50 Lumber production from chip-n-saw (%): 40 Wood chips from sawtimber (%): 30 Wood chips from chip-n-saw (%): 40 Saw dust and fines from sawtimber and chip-n-saw (%): 10 Ratio of paper produced and required green wood: 0.25 GHG emissions related with lumber production (kg CO ₂ e kg ⁻¹): 95 (PRé-Consultants, 2013a) GHG emissions related with paper production (kg CO ₂ e kg ⁻¹): 1353 (PRé-Consultants, 2013b) Non-CO ₂ GHG emissions due to wood waste burning in controlled conditions (kg CO ₂ e kg ⁻¹): 34.4 (WDNR, 2010)
Parameters used during the use phase of wood products
Half-life of lumber (years): 100 (USEIA, 2011) Half-life of paper (years): 2.6 (USEIA, 2011) Recycling rate of lumber (%): 25 (USEIA, 2011) Recycling rate of paper (%): 50 (USEIA, 2011)
Parameters used during the landfill phase of the wood products
Lumber to landfill (%): 76 (USEIA, 2011) Paper to landfill (%): 34 (USEIA, 2011) Lumber changing to non-degradable portion in landfill (%): 77 (USEIA, 2011) Paper changing to non-degradable portion in landfill (%): 44 (USEIA, 2011) Lumber changing to degradable portion in landfill (%): 23 (USEIA, 2011) Paper changing to degradable portion in landfill (%): 56 (USEIA, 2011) Half-life of degradable portion in landfill (years): 14 (USEIA, 2011)

Table 3: Parameters used for ascertaining avoided carbon emissions. Parameters reported in terms of GHG emissions were converted to their carbon equivalent by multiplying them with 12/44.

Bark in green wood (%): 10
Ratio of wood pellets produced and required green wood: 0.5
GHG emissions related with wood pellet production ($\text{kg CO}_2\text{e kg}^{-1}$): 156 (Dwivedi et al., 2011)
GHG intensity of a unit of coal-based electricity in the United Kingdom (g kWh^{-1}): 1018 (Stephenson and MacKay, 2014)
Conversion efficiency of a 100 MW power plant (%): 34 (Argusmedia, 2014)
Calorific value of wood pellet (MJ kg^{-1}): 17 (Argusmedia, 2014)
Electricity transmission losses (%): 6
Distance between Panama City Seaport to the Immingham Seaport (km): 8721
GHGs emissions related with transatlantic transportation of wood pellets ($\text{kg CO}_2 \text{Mg}^{-1} \text{km}^{-1}$): 0.009

Table 4: Range of rotation ages for which additional carbon is saved with respect to the original rotation age at the end of planning horizon.

	Intensive Forest Management								NonIntensive Forest Management							
	LEFT-LR		ENE-LR		ENE-LR+PW		ENE-ALL		LEFT-LR		ENE-LR		ENE-LR+PW		ENE-ALL	
Base Rotation Age	Min Age	Max Age	Min Age	Max Age	Min Age	Max Age	Min Age	Max Age	Min Age	Max Age	Min Age	Max Age	Min Age	Max Age	Min Age	Max Age
10	11	50	11	50	11	46	11	50	11	50	11	50	11	50	11	50
11	12	50	12	50	12	44	12	50	12	50	12	50	12	50	12	50
12	13	50	13	50	13	43	13	50	13	50	13	50	13	50	13	50
13	14	50	14	50	14	43	14	47	14	50	14	50	14	50	14	50
14	15	50	15	50	15	42	15	44	15	50	15	50	15	50	15	50
15	16	50	16	50	16	41	16	42	16	50	16	50	16	50	16	50
16	17	50	17	50	17	40	17	40	17	50	17	50	17	50	17	50
17	18	50	18	50	18	38	18	38	18	50	18	50	18	50	18	50
18	19	50	19	50	19	37	19	36	19	50	19	50	19	50	19	50
19	20	50	20	50	20	36	20	34	20	50	20	50	20	50	20	50
20	21	50	21	50	21	34	21	32	21	50	21	50	21	49	21	50
21	22	50	22	50	22	33	22	31	22	50	22	50	22	48	22	50
22	23	50	23	49	23	32	23	30	23	50	23	50	23	46	23	49
23	24	48	24	47	24	31	24	29	24	50	24	50	24	45	24	47
24	25	46	25	44	25	30	25	28	25	50	25	50	25	44	25	45
25	26	44	26	42	26	29	26	26	26	50	26	50	26	42	26	43
26	27	42	27	40	27	28	-	-	27	50	27	50	27	41	27	41
27	28	40	28	39	-	-	25	26	28	50	28	50	28	39	28	40
28	29	38	29	37	27	27	25	27	29	50	29	50	29	38	29	38
29	30	37	30	36	26	28	24	28	30	50	30	50	30	37	30	37
30	31	35	32	34	25	29	23	29	31	50	31	50	31	35	31	35
31	32	35	30	34	24	30	22	30	32	50	32	50	32	35	32	35
32	33	34	33	33	23	31	21	31	33	50	33	50	33	34	33	34
33	-	-	-	-	22	32	20	32	34	50	34	49	-	-	-	-
34	33	33	32	33	21	33	20	33	35	49	35	47	33	33	33	33
35	32	34	30	34	20	34	19	34	36	47	36	46	32	34	32	34
36	30	35	30	35	20	35	19	35	37	46	37	45	30	35	30	35
37	30	36	29	36	19	36	18	36	38	44	38	43	30	36	30	36
38	29	37	28	37	18	37	18	37	39	43	39	42	29	37	29	37
39	28	38	28	38	17	38	17	38	40	42	40	41	28	38	28	38
40	28	39	27	39	17	39	17	39	41	41	-	-	27	39	28	39
41	27	40	26	40	16	40	16	40	-	-	40	40	27	40	27	40
42	27	41	26	41	15	41	16	41	40	41	39	41	26	41	26	41
43	26	42	25	42	14	42	15	42	39	42	38	42	25	42	26	42
44	26	43	25	43	12	43	15	43	38	43	37	43	25	43	25	43
45	25	44	24	44	11	44	14	44	37	44	37	44	24	44	25	44
46	25	45	24	45	11	45	14	45	37	45	36	45	23	45	24	45
47	24	46	24	46	10	46	14	46	36	46	35	46	22	46	24	46
48	24	47	23	47	10	47	13	47	35	47	34	47	22	47	23	47
49	23	48	23	48	10	48	13	48	35	48	34	48	21	48	23	48
50	23	49	22	49	10	49	13	49	34	49	33	49	20	49	22	49

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5