An Evaluation of Woody Biomass and Pulpwood Market Competition within a Range of Procurement Distances

Manisha Parajuli
Patrick Hiesl
Mathew Smidt
Dana Mitchell

Abstract

In the Southern United States, a rising number of biomass facilities have created new market opportunities for forest landowners, consulting foresters, and loggers, which could increase the competition between the biomass market and pulpwood market for forest biomass. Thus, comparing the profits from conventional roundwood harvesting and biomass harvesting within a range of procurement distances could be crucial to make a harvest decision. In this study, we considered two harvesting systems: conventional and biomass. We developed a decision support tool to predict and compare the final stumpage value from both harvesting systems based on the stand and site conditions, market conditions, and distance to the nearest market. We grew (simulated) loblolly pine (*Pinus taeda*) plantations to six different thinning ages (12, 14, 16, 18, 20, and 22 yr) at five different site indices (17, 20, 23, 26, and 29 m at a base age of 25 yr) using the PTAEDA4.0 software. Different models were fitted and evaluated for certain training and validating criteria. In both harvesting systems, we select the cube root-transformed model as the best model. Using the models, we predict that the utilization of logging residues and pulpwood as wood chips may yield a higher return to the landowner when the delivered price of the wood chips is comparable to the delivered price of the pulpwood and within the same procurement distance. The selected models thus serve as a decision support tool to inform stakeholders to further maximize their economic return from timber harvesting operations by selecting the most profitable option.

The southern United States experienced extensive reforestation efforts between the 1920s and early 2000s (Wakeley 1954, Schultz 1999, Smith et al. 2001, Hernández et al. 2016, South and Harper 2016). Loblolly pine (*Pinus taeda* L.), Slash pine (*P. elliottii* Engelm.), and Longleaf pine (*P. palustris* L.) plantations were a huge success and by the end of the 20th century, the southern United States was recognized as the wood basket of the world (Schultz 1997, Fox et al. 2004). Pine plantations grew vigorously into dense small-diameter stands. It has been reported that a significant portion of pine stands have been neglected over time and that many stands have already passed the first thinning age (Bolding and Lanford 2001, Smith et al. 2001, Gan and Mayfield 2007, Nowak et al. 2015). Thinning is a silvicultural practice of reducing stem density to increase tree vigor and growth while simultaneously reducing fire hazards and disease outbreaks (Haywood 2005, Waldron 2011, Xi et al. 2012). The dense and unmanaged stands, whether natural or planted, accumulate a large amount of biomass and are vulnerable to pest attack and wildfires (Bolding and Lanford 2001, Vogt et al., 2005, Gan and Mayfield 2007, Nowak et al. 2015). In Mississippi, research conducted in 2012 showed that 99.7 percent of the southern pine beetle (*Dendroctonus frontalis*) spots had occurred in unthinned stands, an indication of the vulnerability of unthinned stands to disease outbreak and consequently, an indicator of the importance of thinning to maintain forest health (Nowak et al. 2015). Furthermore, the growth of an

The authors are, respectively, Graduate Research Assistant (mparaju@clemson.edu [corresponding author]) and Assistant Professor of Forest Operations (phiesl@clemson.edu), Clemson Univ., Dept. of Forestry and Environ. Conservation, Clemson, South Carolina; and Research Forester (Mathew.Smidt@usda.gov) and Research Engineer, Project Leader (dana.mitchell@usda.gov), USDA Forest Serv., Southern Research Sta., Forest Operations Research Unit, Auburn, Alabama. This paper was received for publication in May 2021. Article no. FPJ-D-21-00032.

Forest Prod. J. 71(4):407–418.
doi:10.13073/FPJ-D-21-00032

individual tree in a stand is a function of available growing space (Nebeker et al. 1985). The number of trees per hectare has a significant effect on the diameter growth of the individual tree and thus on the value of the final product. If the first thinning is delayed, stand growth and vigor are poor because of the competition between plant roots (Dean and Baldwin 1993). Therefore, if the primary objective is timber production that demands large and quality merchantable stems in the final harvest, the landowner must implement thinning operations to keep trees growing at an acceptable rate (Burton 1982, Dean and Baldwin 1993).

Multiple restoration efforts have been started to convert dense and unmanaged forest stands (planted or naturally regenerated) to historically fire-dependent habitats or return them into working forests after decades of foregone management (Nowak 2004, Rankin and Herbert 2014, Anderson et al. 2016, Anderson and Mitchell 2016, Guldin 2019). Restoration efforts involve the reduction of stand density to increase individual tree growth. A challenge, however, that occurs with these first thinning and restoration cuts is that a large quantity of the trees are unmerchantable and thus require a specialized market to capture some of the stand's economic value (Leinonen 2004, Vogt et al. 2005, Westbrook et al. 2007, Evans 2008).

Traditionally, logging residues from first thinning (low thinning) and restoration cuts are considered unmerchantable for traditional forest products and are left on the forest floor, which increases the risk of forest fire and hinders regeneration (Bolding and Lanford 2001, Leinonen 2004, Perlack et al. 2005, Evans 2008). The annual removal of the total woody biomass from logging operations, precommercial thinning, or from timberland clearing showed that 78 percent of the harvest volume is used as roundwood and the remaining 22 percent is considered as residues (Smith et al. 2004). In the southern United States, around 50 to 85 tonnes (55 to 94 tons) of logging residues remain per hectare following conventional (stem-only) harvesting operations (Eisenbies et al. 2009). This has the potential to yield approximately 32 million tonnes (35 million tons) of dry residues (hog fuel) annually for energy production (Eisenbies et al. 2009). Although the volume of available logging residue is large, the utilization of logging residue as a bioenergy feedstock is in question because of high cut and haul costs and the distance to a market (Bolding 2002, Leinonen 2004, Evans 2008, Smidt et al. 2012, Shabani et al. 2013).

The development and use of mobile chippers have increased the opportunity to recover nonmerchantable stems that would otherwise be left on site (Stokes et al. 1987, Bolding and Lanford 2001, Jernigan et al. 2013). Wood chips produced by these chippers can further be processed to produce wood pellets (Belyakov 2019), a valuable source of bioenergy (Gold 2009, Nickens 2014). Globally, the consumption of wood pellets is increasing and has increased by 60 percent between 2010 and 2016 (Belyakov 2019). The rapid growth of the wood pellet sector in the United States is being driven by the soaring demand for wood pellets in the European market and the United Kingdom (Gold 2009, Joudrey et al. 2012, Voegele 2021). The exportation of US biomass has increased from 94 percent in 2012 to 99.8 percent in the first half of 2015 (Census Bureau 2015). Similarly, the United States has already exported around 10 percent more biomass in the first 2 months of 2021 compared with the biomass available for the same period in 2020 (Voegele 2021). With the increasing concerns about climate change, people may support cleaner energy such as wood-based biofuels (Peksa et al. 2007, Susaeta et al. 2010).

Some of the world's largest pellet manufacturers have been established in the southern United States and account for 46 percent of the total biomass production of the United States (Spelter and Toth 2009). Out of 122 operational wood pellet plants in the United States, 43 are in the southern United States and a new plant has been proposed to be constructed in North Carolina, and three new plants are under construction in other states (Alabama = 2, Mississippi = 1; Voegele 2021). A rising number of biomass facilities have created new market opportunities for landowners, consulting foresters, and loggers, which could discourage the traditional approach of selling pulpwood to a pulpwood mill and may affect the price and availability of traditional pulpwood products (Bowyer 2008, Galik et al. 2009, Conrad et al. 2011, Brandeis and Abt 2019). There has been a decreasing trend of pulp and paper mills in the southern United States such that 29 pulp and paper mills were closed between 1980 and 2005 (Johnson et al. 2008). In 2010, the number of operational pulp and paper mills was 99 (Prestemon et al. 2010), and the number further decreased to 63 in 2020 (primary.forestproductslocator.org). The decreasing number of pulpwood markets suggests that the trucking distance to pulpwood mills from a forest stand may increase. Whereas, with the increasing number of new biomass markets, the probability of the landowners residing within the procurement range of any one of these facilities increases, resulting in shorter trucking distances to a biomass market (Brandeis and Abt 2019).

Transportation costs have been a primary hurdle for the utilization of forest products (Evans 2008, Smidt et al. 2012, Moskalik and Gendek 2019) because they account for 25 to 50 percent of the total stump to mill cost depending upon the price of fuel and haul distance (McDonald et al. 2001, Pan et al. 2007). In the southern United States, the average hauling rate of biomass for a haul distance below 64 km (40 mi; minimum hauling distance) is around US$0.089/tonne/km ($0.13/ton/mi). For distances above 64 km (40 mi), the rate increases to US$0.103/tonne/km ($0.15/ton/mi; Timber-Mart-South 2020). Roundwood quality pulpwood has great potential to be used as a source of energy for the wood energy market, but its viability depends on the market price of the products, price of fossil fuel, and the trucking distance (Perlack et al. 2005, Conrad et al. 2013). When the delivered price of wood chips is comparable to the delivered price of pulpwood, there would be competition between the bioenergy and traditional pulpwood markets (Conrad and Bolding 2011). However, some studies have reported that even if the market price for wood chips is low compared with the pulpwood price, the increasing demand for biomass for bioenergy may cause competition between pulpwood mills and energy companies (Hillring 2006, Benjamin et al. 2009). Some studies have also reported that the utilization of forest biomass for bioenergy development has a great potential for providing extra income to forest landowners (Vogt et al. 2005, Nesbit et al., 2011). In addition, the utilization of unmerchantable products as a source of energy reduces the risk of fire hazards and pest attacks and enhances forest sustainability (Leinonen 2004, Vogt et al. 2005, Richardson 2006, Stephens et al., 2018). Therefore, to promote the use of biomass, the US Department of Energy supports and prioritizes the technology development that produces and utilizes bioenergy (Hartley et al. 2021). Similarly, some other countries are also incorporating bioenergy into their energy policy. For example, in 2019, Georgia's parliament passed a Renewable Energy law to set renewable energy targets (International Energy Agency 2020).

Profitability from harvesting operations can be one of the objectives of landowners. To get a greater economic benefit, it is crucial to supply to the proper markets that allow for the greatest economic return. This could be traditional roundwood markets, bioenergy markets, or a mix of both. Private forest landowners, consulting foresters, and loggers may be interested to compare the stumpage value between conventional roundwood-only harvesting and harvests entailing mainly biomass production. Our study aimed to develop a decision support tool based on the stand and site conditions, market conditions, and a distance to the nearest market to inform stakeholders about options to further maximize their economic return from timber harvesting operations.

Methods

Loblolly pine stand simulations

Loblolly pine is the most widely planted species in the southeastern United States (McKeand et al. 2003). For this study, we used a simulation approach to estimate harvest volumes in first thinning for a range of stand ages and site indices. Loblolly pine stands and individual tree growth were simulated using the growth and yield simulator PTAEDA4.0, software developed to specifically model growth in loblolly pine plantation stands (Burkhart et al. 2008). We grew (simulated) loblolly pine plantations to six different thinning ages (12, 14, 16, 18, 20, and 22 yr) on five different site indices 17, 20, 23, 26, and 29 meters at a base age of 25 years (55, 65, 75, 85, and 95 ft at a base age of 25 yr) for the Piedmont physiographic region. Our simulation used a 2.44-meters by 2.44-meters (8-ft by 8-ft) planting spacing with a stand density ranging from 1,653 trees/ha to 1,712 trees/ha (669 to 693 trees/acre). We used this spacing to represent plantations that may have been established 12 to 22 years ago (from the 1990s to 2010s) that utilized such spacing and are now in need of a first thinning. All the simulated sites consisted of well-drained soils, chop and burn site preparation, no application of fertilizer, and a combination of fifth row thinning and thinning from below for the first thinning. Each simulated stand was thinned to a residual basal area of 18 m^2/ha (80 square ft/acre; Brown et al. 1987, Fettig et al. 2007, Nowak et al. 2008). We recorded the stand density before and after the thinning, and calculated removal volumes for the total biomass, pulpwood, Chip-N-Saw, and sawtimber for each simulated stand. The minimum merchandising diameters at breast height (dbh) for pulpwood, Chip-N-Saw, and sawtimber were used as 12.7 cm, 20.32 cm, and 30.48 cm (5″, 8″, and 12″), respectively. Similarly, the top diameter (outside bark) limits for pulpwood, Chip-N-Saw, and sawtimber were 7.62 cm, 17.78 cm, and 25.5 cm (3″, 7″, and 10″), respectively. Based on our interaction with mills in South Carolina, the above specifications are common. However, we acknowledge that some mills and regions may have smaller diameter specifications for the same products. Residual biomass (tops and limbs) volume was calculated by subtracting pulpwood, Chip-N-Saw, and sawtimber volumes from the total volume provided by PTAEDA4.0. No volume was recorded for any voluntary ingrowth. All data were recorded in a Microsoft Excel file.

Harvesting systems

For this study, we considered two different harvesting systems. The first system (conventional–roundwood system) is a whole-tree harvesting system using a drive-to-tree feller-buncher, grapple skidder, trailer-mounted loader, and pull-through delimber. The utilization rate of the equipment was not taken into account in the simulation. For the whole-tree harvesting system, we assumed that all roundwood was delivered to the appropriate pulpwood mill, Chip-N-Saw mill, and sawtimber mill and that any residual biomass was left in the forest. The second system (biomass system–fuel chip production) uses the same machines as the conventional system with the addition of a mobile chipper. For this system, we assumed that all the pulpwood and low-value tops and limbs were chipped and delivered to a biomass market as fuel chips. Chip-N-Saw and sawtimber were assumed to be delivered to their respective mills as roundwood products.

Cost and revenue calculation

The Excel sheet with the stand and volume information was imported into the statistical software package R 3.6.0 (R Core Team 2019) for cost and revenue calculations. We estimated the thinning, chipping, and trucking costs, as well as revenue and stumpage values for each system, thinning age, and site index combination. In the conventional system, thinning cost of pulpwood was calculated by multiplying pulpwood volume by the average south-wide cut and load rate (Table 1). The cut and load rate is an amount paid for felling, skidding, and loading, and was based on the first quarter report of TimberMart-South (TimberMart-South 2020). Similarly, Chip-N-Saw and sawtimber thinning costs were calculated using the respective product volume multiplied by the cut and load rate. In the biomass system, the chipping cost was calculated using the pulpwood thinning cost calculated for the conventional system and adding the product when multiplying the total volume of pulpwood, tops, and limbs by the chipping rate (Table 1) to account for the cost of the mobile chipper. The chipping rate was estimated based on information obtained from personal communication with professors and loggers in South Carolina and Alabama. For hauling distances of $\leq$64 km (40 mi), the transportation cost was calculated by multiplying the volume of all products by the minimum haul distance of 64 km (40 mi) and the minimum haul rate of US\$0.089/tonne/km (\$0.13/ton/mi). For distances $>$64 km (40 mi), we added an incremental charge using the distance above 64 km multiplied with the incremental haul rate of US\$0.103/tonne/km (\$0.15/ton/mi). The revenue from each system was calculated by multiplying the volume of the respective products by its mill delivered price (Table 1). We used a range of input values for all calculations but kept the mill-delivered price of Chip-N-Saw and sawtimber, distance to Chip-N-Saw mill, and distance to sawtimber mill constant (Table 1). In the conventional system, the total stumpage value was obtained by subtracting thinning cost and trucking cost from the revenue of the respective products. In the biomass system, the total stumpage value was obtained by subtracting thinning cost, chipping cost, and trucking cost from the revenue of the respective products.

Table 1.—Range of input values used for cost, revenue, and stumpage calculations for conventional and biomass systems, where the average of the input values was referenced from TimberMart-South first quarter of 2020 (TimberMart-South 2020). The wide range of input values for the calculations was used to account for the variation that may result from the site-specific condition. Values presented in parentheses show the English units used for the underlying simulation.

Variables	Minimum value	Maximum value	Increment
Cut and load rate US$/tonne ($/ton)	12.12 (11)	14.33 (13)	1.102 (1)
Chipping rate US$/tonne ($/ton)	2.20 (2)	4.41 (4)	1.102 (1)
Pulpwood mill delivered price US$/tonne ($/ton)	24.24 (22)	35.26 (32)	2.204 (2)
Wood chips (fuel chips) delivered price US$/tonne ($/ton)	22.04 (20)	35.27 (32)	2.204 (2)
Chip-N-Saw mill delivered price US$/tonne ($/ton)	38.58 (35)	38.58 (35)	—
Sawtimber mill delivered price US$/tonne ($/ton)	46.28 (42)	46.28 (42)	—
Distance to pulpwood mill km (mi)	64 (40)	225 (140)	32 (20)
Distance to biomass market km (mi)	64 (40)	129 (80)	32 (20)
Distance to Chip-N-Saw mill km (mi)	97 (60)	97 (60)	—
Distance to sawtimber mill km (mi)	97 (60)	97 (60)	—

For both systems, we also deducted a procurement commission of US$2.20/tonne ($2/ton).

We used the high-performance computing Palmetto cluster at Clemson University to facilitate the calculations for the given range of input variables. All simulations and calculations were carried out in English units and later were converted to metric units using the following conversion factors: 1 mile = 1.609 km, 1 ton = 0.907 tonnes, 1 acre = 0.405 hectares.

Model development and selection

For each harvesting system, we developed one linear regression model to predict a stumpage value (dollars per hectare) based on a set of independent variables. The independent variables used in the conventional system were the volume of pulpwood, Chip-N-Saw, and sawtimber; site index; thinning age; cut and load rate; pulpwood delivered price; Chip-N-Saw delivered price; sawtimber delivered price; distance to pulpwood mill; distance to Chip-N-Saw mill; and distance to sawtimber mill. The independent variables used in the biomass system were the volume of wood chips (fuel chips), Chip-N-Saw, and sawtimber, site index, thinning age, cut and load rate, chipping rate, wood chips delivered price, Chip-N-Saw delivered price, sawtimber delivered price, distance to biomass market, distance to Chip-N-Saw mill, and distance to sawtimber mill. We calculated the measure of central tendency and dispersion of all the variables. Scatter plots were used to check whether the relationships between independent and dependent variables were linear. We assumed that our large simulated data (1,428,840 observations per system) was normally distributed (Kwak and Kim 2017). We performed backward elimination to find the significant variables. A constant value of US$1,005/ha ($408/acre) and US$1,000/ha ($405/acre) was added to the dependent variable in the conventional and biomass systems, respectively, to turn any negative values into positive values. To improve the homoscedasticity of variance, we applied common transformations: square root, log, and cube root to the dependent variable. Multicollinearity was tested to remove variables that were highly correlated (Pearson's $r > 0.60$; Mcgregor et al. 2012).

A cross-validation approach was carried out to check the performance of the models on new data sets. In each system, the data were split into two parts: 75 percent of the data (training set) were randomly selected to develop the models, while the remaining 25 percent of data (test set) were used for model validation. For the training data set, the goodness-of-fit statistics for models such as the significance of parameter estimates, coefficient of determination R^2, and root mean square error (RMSE) were assessed. We used a 10-fold cross-validation approach for parameter optimization (Kohavi 1995, Liski et al. 2020) and RMSE was selected as a criterion for model selection (Liski et al. 2020). The prediction error of the test set was compared for evaluating the prediction ability of the models. For each system, the best-fitted model on both stages (i.e., training and validation) were selected and was fitted to the full data set to develop final models (Liski et al. 2020). The ordinary least-square method was used at an alpha level of 0.05 (Koirala et al. 2017) using statistical package R 3.6.0. Models were back-transformed to the original units.

Model comparison

The predicted stumpage values from the two final models were compared graphically based on the distance to the pulpwood or biomass market, delivered prices of the products, and the cut and load rates. We selected a site index of 23 meters at a base age of 25 (75 ft at a base age of 25), a cut and load rate of US$13.22/tonne ($12/ton), and a chipping rate of US$3.31/tonne ($3/ton) for graphical evaluation. We assumed that the cut and load rate remained constant regardless of the distance and that every contractor has access to unlimited trucks. These values thus serve as an example of the applicability of the models and any other combination of input values can be generated using the presented models. For visual comparison, first, we changed the delivered price of roundwood and wood chips such that the price of the wood chips was once lower than, equal to, and higher than the pulpwood delivered price. Later, we increased the distance to the biomass market and compared the results. In the figures, the intersection of the two lines (conventional system and biomass system) shows at which distance to the biomass and pulpwood market the stumpage value of the conventional and biomass system are equal. The figures are examples of some of the extremes that maybe happening in the industry.

Results

Simulation of the pine plantation stand resulted in 1,428,840 observations per system. An increase in the thinning age of the stands resulted in a larger volume of the harvested products.

Conventional system

Results of the multicollinearity test showed that pulpwood volume, Chip-N-Saw volume, and sawtimber volume were highly correlated with site index and thinning age (r $>$0.6). We choose site index and thinning age as our predictor variables instead of the product volumes because these variables are commonly available to foresters before harvesting. We removed Chip-N-Saw distance, sawtimber distance, Chip-N-Saw delivered price, and sawtimber delivered price because the value of these variables was kept constant. In the conventional system, site index (SI), thinning age (TA), cut and load rate (CLR), distance to a pulpwood mill (PD), and pulpwood mill delivered price (PDP) were significant predictors (P $<$0.05) and were selected for model development. The cube root-transformed model (M3; Eq. 1; Table 2) was selected amongst other candidate models based on statistical evidence. The adjusted R^2 of the square root-transformed model (M1) and M3 was higher than that of log-transformed model (M2). The prediction error of M2 and M3 was lower than M1. However, RMSE and Mean Absolute Error (MAE) of M3 were lowest followed by the M2 and M1 (Table 3).

$$\begin{aligned} &Stumpage(\$/hectare) \\ &\quad = (4.231 + 0.0559 \times SI + 0.2025 \times TA - 0.2642 \\ &\qquad \times CLR - 0.0204 \times PD + 0.2015 \times PDP)^3 - 1005 \end{aligned} \tag{1}$$

Biomass system

We used site index and thinning age as our predictor variables in lieu of the actual volumes because wood chips volume, Chip-N-Saw volume, sawtimber volume, and top wood volumes were highly correlated with the site index and thinning age (r $>$0.6). In the biomass system, site index (SI), thinning age (TA), cut and load rate (CLR), chipping rate (CR), distance to the biomass market (CD), and wood chips delivered price (CDP) were significant predictors (P $<$0.05) and were selected for model development. The cube root-transformed model (M6; Eq. 2; Table 4) was selected amongst other candidate models based on statistical evidence. The adjusted R^2 of M6 and log-transformed model (M5) was equal and slightly higher than the square root-transformed model (M4). The prediction error of M5 was lowest followed by M6 and M4. However, RMSE and MAE of M6 were lowest followed by M5 and M4 (Table 5).

$$\begin{aligned} &Stumpage(\$/hectare) \\ &\quad = (3.963 + 0.0587 \times SI + 0.2114 \times TA - 0.2361 \times CLR \\ &\qquad - 0.1981 \times CR - 0.0202 \times CD + 0.1952 \times CDP)^3 \\ &\qquad - 1000 \end{aligned} \tag{2}$$

Table 2.—Result showing the predictor variables affecting stumpage value of the conventional system.

	Estimate	Standard error	Pr(>|t|)
Intercept	4.231	0.01096	<0.001
Site Index (SI)	0.0559	0.0000421	<0.001
Thinning Age (TA)	0.2025	0.0001742	<0.001
Cut and Load Rate (CLR)	−0.2642	0.0006614	<0.001
Distance to Pulpwood Mill (PD)	−0.0204	0.00001083	<0.001
Pulpwood Mill Delivered Price (PDP)	0.2015	0.0001574	<0.001

Table 3.—Final statistical value of models in the conventional system. RMSE is root mean square error. MAE is mean absolute error.

Model transformation	Adjusted R^2	RMSE	MAE	Prediction error
Square root (M1)	0.85	12.92	7.0	0.43
Log (M2)	0.81	1.25	1.1	0.41
Cube root (M3)	0.85	0.36	0.13	0.41

Biomass value less than pulpwood value

When the delivered price of biomass was less than the delivered price of pulpwood and a distance to a pulpwood mill was >124 km (77 mi) for a thinning age of 22 years and 127 km (79 mi) for a thinning age of 12 years with the nearest biomass market within 64 km (40 mi), we found that the highest economic return was achieved by using the biomass system and chipping all pulpwood, tops, and limbs (Fig. 1). Between ages of 12 years to 22 years, the stumpage value showed a direct relationship with the thinning age of the stand. Similarly, when the thinning age increased, the point at which the stumpage value from conventional system and biomass system became equal shift toward left, which indicates that at a higher thinning age biomass system is comparatively more profitable.

When the distance to the nearest biomass market was increased from 64 to 97 km (40 to 60 mi; Fig. 2), the stumpage value from the biomass system decreased by an average of 54 percent and the percentage decrease was higher at lower thinning ages (113% at a thinning age of 12 yr to 29% at a thinning age of 22 yr). As the stumpage value from the biomass system decreased, the conventional system was a better option for a distance to a pulpwood mill of up to 154 km (96 mi) for a thinning age of 22 years and up to 158 km (98 mi) for a thinning age 12 years. However, when the pulpwood mill was farther away than that, the economic return was greater with the biomass system.

Table 4.—Result showing the predictor variables affecting stumpage value of the biomass system.

	Estimate	Standard error	Pr(>|t|)
Intercept	3.963	0.007692	<0.001
Site Index (SI)	0.0587	0.00002953	<0.001
Thinning Age (TA)	0.2114	0.0001223	<0.001
Cut and Load Rate (CLR)	−0.2361	0.0004642	<0.001
Chipping Rate (CR)	−0.1981	0.0004642	<0.001
Distance to Biomass Market (CD)	−0.0202	0.00001590	<0.001
Wood Chips Delivered Price (CDP)	0.1952	0.00009475	<0.001

Table 5.—Final statistical value of models in the biomass system. RMSE is root mean square errors. MAE is mean absolute error.

Model transformation	Adjusted R^2	RMSE	MAE	Prediction error
Square root (M4)	0.89	7.34	4.21	1.36
Log (M5)	0.90	1.13	1.09	1.34
Cube root (M6)	0.90	0.12	0.05	1.35

Biomass value equal to pulpwood value

When the delivered price of biomass was equal to the delivered price of pulpwood with a distance to a pulpwood mill >81 km (50 mi) for a thinning age of 22 years and >83 km (52 mi) for a thinning age of 12 years and the nearest biomass market within 64 km (40 mi), we found that the greatest economic return was achieved by chipping all pulpwood roundwood and tops or limbs (Fig. 3).

When the distance to the nearest biomass market was increased from 64 to 97 km (40 to 60 mi; Fig. 4), the stumpage value from the biomass production decreased by an average of 28 percent and the percentage decrease was higher at lower thinning ages (39% at a thinning age of 12 yr to 21% at a thinning age of 22 yr). As the stumpage value from biomass production decreased, the conventional system was a better option for a distance to a pulpwood mill of up to 115 km (71 mi) for a thinning age of 22 years and up to 118 km (73 mi) for a thinning age of 12 years. However, when the pulpwood mill was farther away than that, the economic return was greater with the biomass system.

Biomass value higher than pulpwood value

When the delivered price of biomass was higher than the delivered price of pulpwood, given a distance to the nearest biomass market was within 64 km (40 mi), the biomass system achieved the greatest economic return at any distance to the pulpwood mill (Fig. 5). When the distance to the nearest biomass market was increased from 64 to 97 km (40 to 60 mi; Fig. 6), the stumpage value from the biomass production decreased by an average of 22 percent. The percentage decrease was higher at lower thinning ages (28% at a thinning age of 12 yr to 18% at a thinning age of 22 yr). As the stumpage value from wood chip production decreased, the conventional system was a better option for a distance to a pulpwood mill of up to 70 km (43 mi) for a thinning age of 22 years and up to 73 km (45 mi) for a thinning age of 12 years. However, when the pulpwood mill was further than that, the economic return was greater with the biomass system.

Discussion

Many studies in the past had not taken into consideration the volume of logging residues and the economic profitability from the utilization of those logging residues. The decision to utilize the logging residues for wood chips production is based on several factors such as delivered price, trucking distance, chipping rate, and cut and load rate. In a typical first thinning of loblolly pine stands ranging from age 13 to 18 years, around 72 percent of the total yield was roundwood and the remaining 28 percent was logging residues (Stokes 1998). Some studies reported that the harvesting of logging residue is not suitable for thinning operation because the revenue from selling those materials may not offset the high processing and transportation costs (Withycombe 1982, Bolding 2002, Han et al. 2004, Shabani et al. 2013, Kizha et al. 2015). However, our study shows that when thinning was assigned on pine stands between the ages of 12 and 22 years, it produced a considerable volume of top and limb materials. Therefore, the utilization of logging residues and pulpwood for wood chip production may yield a higher return to the landowner when the delivered price of the wood chips is comparable to the delivered price of the pulpwood and within the same procurement distance.

The profits from any harvest type are expected to increase with higher product prices (Han et al. 2004). Historically, in the southern United States, wood chips are worth less than pulpwood (TimberMart-South 2010, 2020). In the first quarter of 2020, the delivered price of wood chips was US$25.43/tonne ($23/ton) compared with US$32.45/tonne ($29/ton) for pulpwood. Biomass prices would have to be

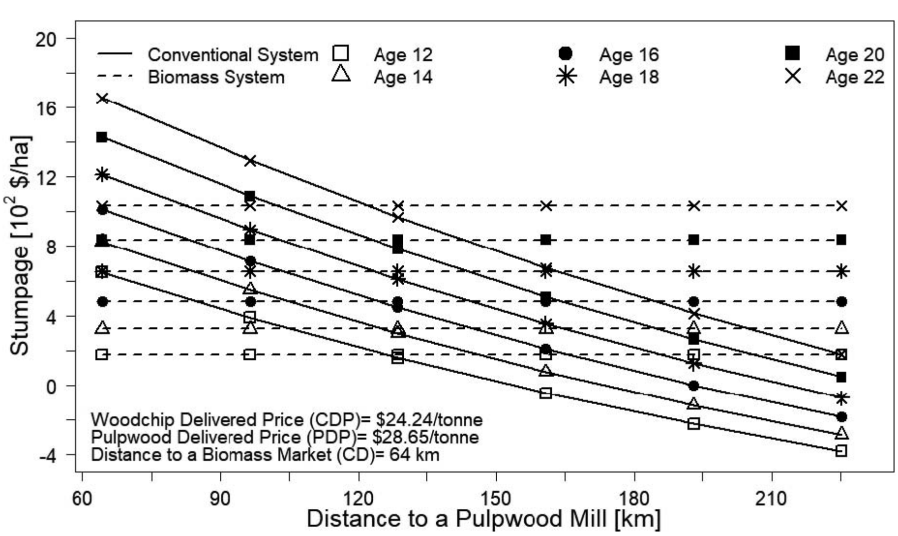

Figure 1.—Estimated stumpage values for the conventional and biomass harvesting systems for a biomass value lower than pulpwood value and a distance to a biomass market of 64 km (40 mi).

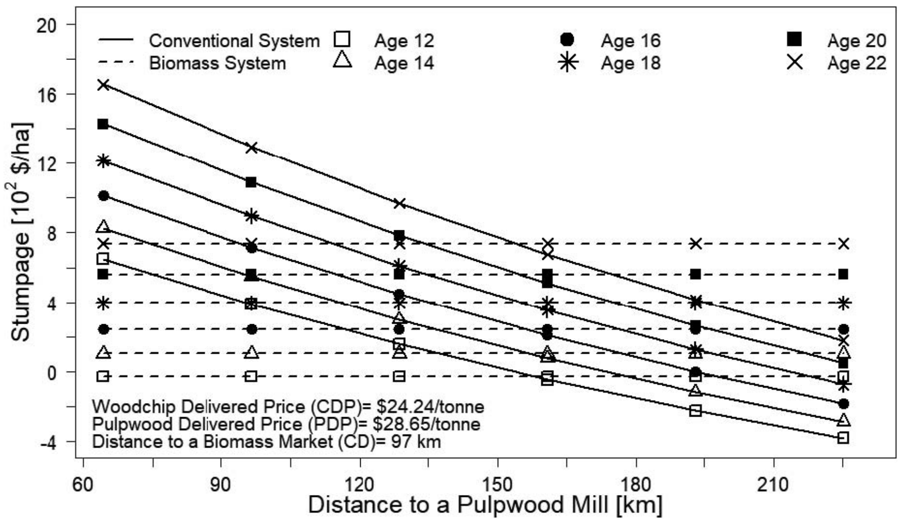

Figure 2.—Estimated stumpage values between the conventional and biomass harvesting systems for a biomass value lower than pulpwood value and a distance to a biomass market of 97 km (60 mi).

increased by 26 percent to compete with the pulpwood market. Although it incurs additional chipping costs, in-woods whole-tree chipping saves time, labor, and operational cost associated with delimbing, topping, and bucking at the landing for pulpwood production (Conrad and Bolding 2011). When the delivered price of woody biomass chips is comparable to the delivered price of pulpwood, the landowner maybe indifferent to do either a traditional or biomass harvest (Kumarappan et al. 2009, Conrad and Bolding 2011, Conrad et al. 2013). Similarly, in areas with a lower pulpwood delivered price than biomass price, it can be beneficial to merchandise all pulpwood as wood chips if the transportation distance to the pulpwood mill is significantly longer than the distance to the biomass market.

Companies are demanding a larger volume of wood chips than in the previous years because of the increasing number of biomass and pellet demands in the European market (Hillring 2006). With the increasing demand, a larger volume of roundwood is being converted into wood chips for wood pellet production (Brandeis and Abt 2019). Some of the pellet manufacturers pay higher prices for wood chips than for roundwood but demand that the wood chips are separated by softwood and hardwood species. They lower their expenses by not having to chip roundwood themselves and pass along that cost saving to the logger to pay for the in-woods chipping (J. Deason, personal communication, April 2021). In addition, sawmill residues from the primary wood products industry are also being used as a feedstock for wood pellet production (Belyakov 2019). As the southern wood pellet facilities are increasing their capacity, landowners and timber buyers have also shown an increasing interest in the bioenergy market. A study by Conrad et al. (2011) reported that 90 percent of the landowners are willing to sell the wood to the energy facilities if they get a good price. Similarly, many timber buyers may be willing to pay high prices for wood-based biofuels, giving landowners more profit to invest (Susaeta et al. 2010). However, the availability of mobile chippers is

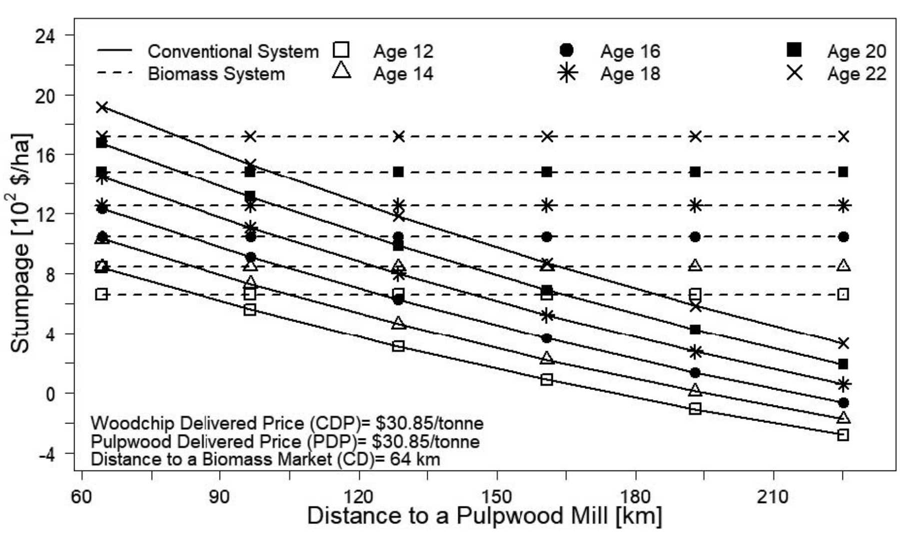

Figure 3.—Estimated stumpage values for the conventional and biomass harvesting systems for a biomass value equal to pulpwood value and a distance to a biomass market of 64 km (40 mi).

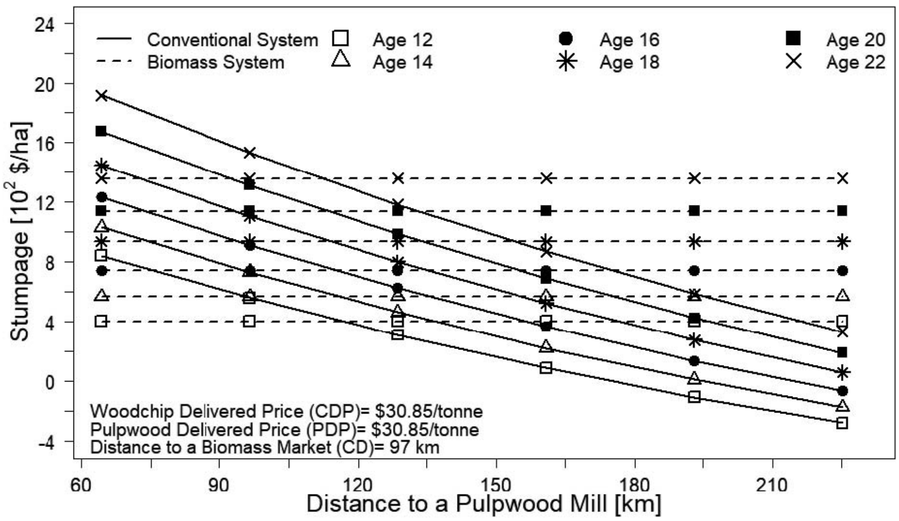

Figure 4.—Estimated stumpage values for the conventional and biomass harvesting systems for a biomass value equal to pulpwood value and a distance to a biomass market of 97 km (60 mi).

limited, with recent logging business surveys in Georgia, South Carolina, and Virginia indicating that less than 20 percent of logging businesses own a mobile chipper (Barrett et al. 2017, Conrad et al. 2018). Nonetheless, Conrad et al. (2018) also showed that there was a 4 percent increase in the number of logging businesses that owned a mobile chipper, suggesting that with an increase in biomass markets there will be an increase in mobile chipper availability.

The profit from the extraction and use of pulpwood, biomass, or whole-tree wood chips was found to be highly associated with transportation distance (Smidt et al. 2012, Pokharel et al. 2019). We found that when the distance to the pulp mill or biomass market increased, the transportation cost increased, and the stumpage value of the respective system decreased. Therefore, the distance to the biomass facilities and the associated trucking costs can significantly affect the profitability of a conventional or biomass harvesting system. Many studies mentioned that if the facilities that utilize the biomass are near the harvested site, it makes biomass harvesting economical (Han et al. 2004, Harrill and Han 2012). Currently, the growing demand for biomass from energy facilities has increased the number of markets and reduced the distance to those markets for many landowners. Our results show that if the biomass market is within 64 km (40 mi) and the wood chips delivered price is higher than the pulpwood delivered price, it is more profitable to utilize a biomass harvesting system. However, the higher stumpage value for the biomass system may be due to an underestimation of roundwood volume in the conventional system, given that we used conservative log-size restrictions. Individual markets may have different specifications for the size restrictions of roundwood products and thus result in potentially different outcomes. Legal truck weights can differ by state, e.g., a log truck may weigh 38,101 kg (84,000 lbs) in Georgia (Conrad 2018), 38,225 kg (84,272 lbs) in South Carolina (South Carolina Code of Laws 2021), 40,823 kg (90,000 lbs) in Virginia (Public Law Virginia House Bill 2072 2015) and North

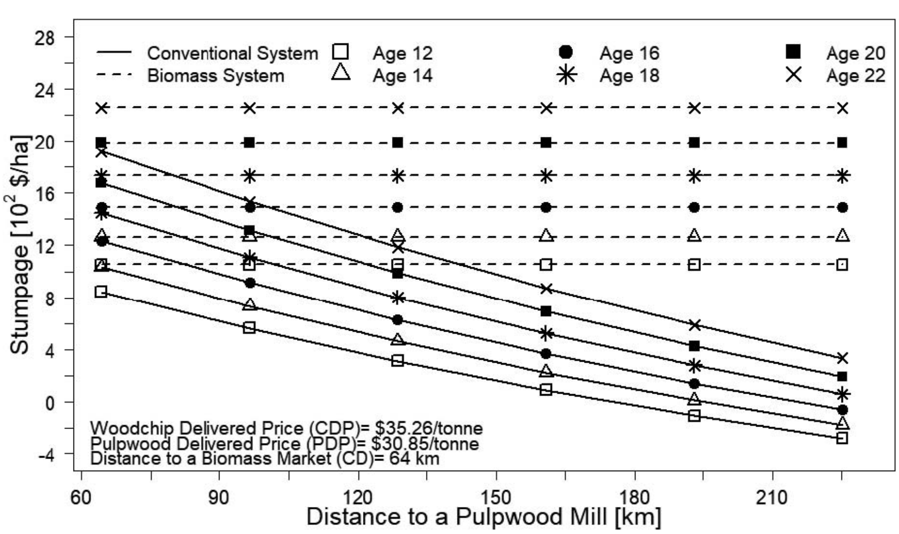

Figure 5.—Estimated stumpage values for the conventional and biomass harvesting systems for a biomass value higher than pulpwood value and a distance to a biomass market of 64 km (40 mi).

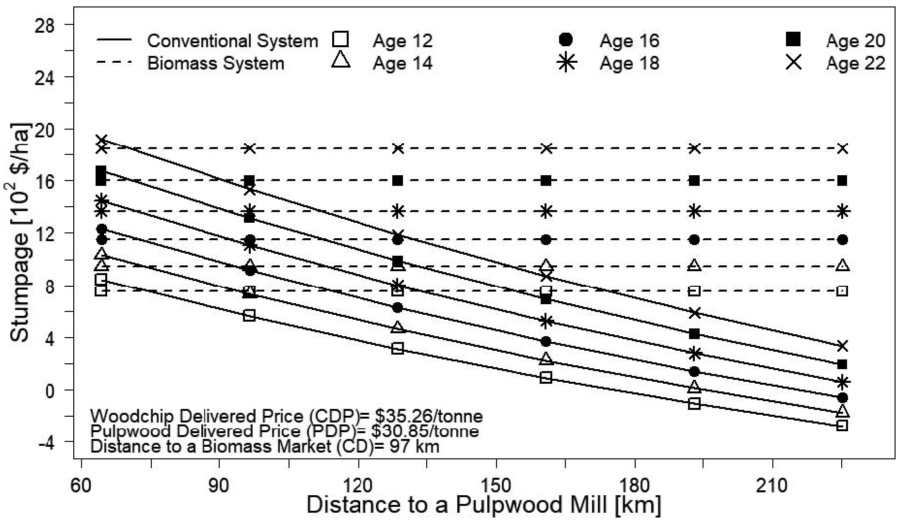

Figure 6.—Estimated stumpage values for the conventional and biomass harvesting systems for a biomass value higher than pulpwood value and a distance to a biomass market of 97 km (60 mi).

Carolina (Public Law North Carolina Session Law 2012-78 2012), or as much as 41,730 kg (92,000 lbs) in Louisiana (Public Law Louisiana Act 84 2020). Our simulation did not take into account specific truck load weights but rather based its estimates on the total volume. The results from our models should thus be used as a guidance to further investigate the economic feasibility of one system over the other.

The utilization of logging residues produced from thinning and restoration cuts as wood chips for bioenergy production could be a profitable option. In addition, the utilization of logging residue produced from thinning and restoration cuts may help to reduce the forest fire risk, decrease site preparation cost, and support forest regeneration (Leinonen 2004, Wear and Greis 2012, Xi et al. 2012). However, the way timber is bought and sold varies between states and regions and the utilization of logging residues depends on the interest of landowners and timber buyers. In the southern United States, a typical thinning will be made on a pay-as-cut basis and the landowner will be paid an agreed-upon stumpage price per ton for each product (Grove et al. 2020). Although the destination of the pulpwood-sized material is determined by the timber buyer, the landowner may enjoy a ''cleaner'' site following in-wood chipping, which might indicate a greater chance toward accepting a bid from a timber buyer that aims to chip energy wood. The National Woodland Owners Survey has shown that more than 60 percent of the family forest ownerships value their forest land for their beauty, suggesting that these forest owners may prefer the cleaner look that a chipping operation can provide (Butler et al. 2016).

Conclusion

Site index, thinning age, cut and load rate, chipping rate, delivered price of products, and the trucking distance to markets are the factors affecting the stumpage value of the harvesting systems. When deciding to select between two harvesting systems, landowners, consulting foresters, and loggers must consider these factors. When the delivered price of biomass is lower than, equal to, or higher than the delivered price of the pulpwood, it may be beneficial to decide on a harvesting system based on the trucking distance to the nearest pulpwood mill or biomass market. If a biomass market is available in the local area, it could be profitable to do biomass harvesting even if the biomass value is lower than the pulpwood value.

Furthermore, the cut and load rate, chipping rate, delivered price, and trucking distance may differ from one place to another. Similarly, these rates may also change over time. The models are useful as a decision support tool to estimate the stumpage value from conventional and biomass harvests based on the stand and site conditions, market conditions, and the distance to markets. These models may further inform forest stakeholders about options to further maximize their economic return from timber harvesting operations.

Acknowledgment

We would like to thank US Forest Service, Southern Research Station in Auburn, Alabama, for funding this project through a joint-venture agreement (19-JV-11330132-087), as well as Clemson University for generous allotment of compute time on Palmetto cluster.

Literature Cited

Anderson, N. and D. Mitchell. 2016. Forest operations and woody biomass logistics to improve efficiency, value, and sustainability. *Bioenergy Res*. *9*(2):518–533. DO:10.1007/s12155-016-9735-1

Anderson, Hayes, L., P. D. Keyser, C. M. Lituma, R. D. Sutter, and D. Zollner. 2016. Shortleaf pine restoration plan: Restoring an American forest legacy. Shortleaf Pine Initiative, Knoxville, TN.

Barrett, S. M., M. C. Bolding, and J. F. Munsell. 2017. Characteristics of logging businesses across Virginia's diverse physiographic regions. *Forests* 8(12). DOI:10.3390/f8120468

Belyakov, N. 2019. Sustainable Power Generation: Current Status, Future Challenges, and Perspectives. Academic Press, Cambridge, Massachusetts.

Benjamin, J., R. J. Lilieholm, and D. Damery. 2009. Challenges and opportunities for the northeastern forest bioindustry. *J. Forestry* 107(3):125–131. DOI:10.1093/jof/107.3.125

Bolding, M. C. 2002. *Forest fuel reduction and energywood production using a CTL/smaller chipper harvesting system*. Master's thesis. Auburn University, Auburn, Alabama.

Bolding, M. C. and B. L. Lanford. 2001. Forest fuel reduction through energy wood production using a small chipper/CTL harvesting system.

In: Appalachian Hardwoods; Managing Change. Proceedings of the 24th Annual Council on Forest Engineering Meeting; J. Wang, M. Wolford, and J. McNeel (Eds.); July 15–19, 2001; Snowshoe, West Virginia. Council on Forest Engineering 65-7, Corvallis, Oregon.

Bowyer, J. L. 2008. The green movement and the forest products industry. *Forest Prod. J*. 58(7):6.

Brandeis, C. and K. L. Abt. 2019. Roundwood use by southern wood pellet mills: Findings from timber product output mill surveys. *J. Forestry* 117(5):427–434. DOI:10.1093/jofore/fvz042

Brown, M., T. Nebeker, and C. Honea. 1987. Thinning increases loblolly pine vigor and resistance to bark beetles. *South. J. Appl. Forestry* 11:28–31.

Burkhart, H. E., R. L. Amateis, J. A. Westfall, and R. F. Daniels. 2008. PTAEDA4.0: Simulation of individual tree growth, stand development and economic evaluation in loblolly pine plantations. User Manual, 27. Department of Forestry, Virginia Tech, Blacksburg, Virginia. https://fmrc.frec.vt.edu/content/dam/fmrc_frec_vt_edu/documents/ptaeda4.0%20manual.pdf. Accessed October 20, 2021.

Burton, J. D. 1982. Sawtimber by prescription—The sudden sawlog story through age 33. Research Paper SO-179. US Department of Agriculture, Forest Service, Southern Forest Experiment Station, New Orleans, Louisiana.

Butler, B. J., J. H. Hewes, B. J. Dickinson, K. Andrejczyk, M. Markowski-Lindsay, and S. Butler. 2016. Family forest ownerships of the United States, 2013: Tabular results from the USDA forest service, national woodland owner survey. *Dept. Agric., Forest Serv., North. Res. Stn*. 114(November):638–647.

Census Bureau. 2015. USA Trade. US Department of Commerce, Washington, D.C.

Conrad, J. L. 2018. Costs and challenges of log truck transportation in Georgia, USA. *Forests* 9(10). DOI:10.3390/f9100650

Conrad, J. L., and M. C. Bolding. 2011. Virginia's woody biomass market: Opportunities and implications. *South. J. Appl. Forestry* 35(2):67–72. DOI:10.1093/sjaf/35.2.67

Conrad, J. L., M. C. Bolding, W. M. Aust, R. L. Smith, and A. Horcher. 2013. Harvesting productivity and costs when utilizing energywood from pine plantations of the southern Coastal Plain USA. *Biomass and Bioenergy* 52:85–95. DOI:10.1016/j.biombioe.2013.02.038

Conrad, J. L., M. C. Bolding, R. L. Smith, and W. M. Aust. 2011. Wood-energy market impact on competition, procurement practices, and profitability of landowners and forest products industry in the U.S. south. *Biomass and Bioenergy* 35(1):280–287. DOI:10.1016/j.biombioe.2010.08.038

Conrad, J. L., W. D. Greene, and P. Hiesl. 2018. The evolution of logging businesses in Georgia 1987–2017 and South Carolina 2012–2017. *Forest Sci*. 64(6):671–681.

Dean, T. and V. C. J. Baldwin. 1993. Using a density-management diagram to develop thinning schedules for loblolly pine plantations. Research Paper SO-275. New Orleans, LA: US Department of Agriculture, Forest Service, Southern Forest Experiment Station, New Orleans, Louisiana.

Eisenbies, M. H., E. D. Vance, W. M. Aust, and J. R. Seiler. 2009. Intensive utilization of harvest residues in southern pine plantations: Quantities available and implications for nutrient budgets and sustainable site productivity. *Bioenergy Res*. 2(3):90–98. DOI:10.1007/s12155-009-9036-z

Evans, A. M. 2008. *Synthesis of Knowledge from Woody Biomass Removal Case Studies* 36. US Department of Agriculture, Forest Service, Forest Guild, Santa Fe, New Mexico. https://www.firescience.gov/projects/07-3-2-02/project/07-3-2-02_07_3_2_02_biomass_case_studies_report.pdf. Accessed October 20, 2021.

Fettig, C. J., K. D. Klepzig, R. F. Billings, A. S. Munson, T. E. Nebeker, J. F. Negrón, and J. Nowak. 2007. The effectiveness of vegetation management practices for prevention and control of bark beetle infestations in coniferous forests of the western and southern United States. *Forest Ecol. Manag*. 238(1–3):24–53. DOI:10.1016/j.foreco.2006.10.011

Fox, T. R., E. J. Jokela, and H. L. Allen. 2004. Pine plantation silviculture. General Technical Report SRS–75. US Department of Agriculture, Forest Service, Southern Research Station, Asheville, North Carolina. pp. 63–82.

Galik, C. S., R. Abt, and Y. Wu. 2009. Forest biomass supply in the southeastern United States—Implications for industrial roundwood and bioenergy production. *J. Forestry* 107(2):69–77.

Gan, J. and C. Mayfield. 2007. Forest bioenergy production and rural economic development. *In:* Sustainable Forestry for Bioenergy and Bio-Based Products: Trainer's Curriculum Notebook. W. Hubbard, L. Biles, C. Mayfield, and S. Ashton (Eds.). Southern Forest Research Partnership, Inc., Athens, Georgia. pp. 217–220.

Gold, R. 2009. Wood pellets catch fire as renewable energy source. *The Wall Street J*. July 7, 2009. https://www.wsj.com/articles/SB124691728110402383. Accessed October 20, 2021.

Grove, P. M., J. L. Conrad, T. G. Harris, and J. Dahlen. 2020. Consulting forester timber sale practices in the US south. *Forest Sci*. 66(2):221–229. DOI:10.1093/forsci/fxz068

Guldin, J. M. 2019. Restoration of native fire-adapted southern pine-dominated forest ecosystems: Diversifying the tools in the silvicultural toolbox. *Forest Sci*. *65*(4):508–518. DOI:10.1093/forsci/fxz005

Han, H.-S., H. W. Lee, and L. R. Johnson. 2004. Economic feasibility of an integrated harvesting system for small-diameter trees in southwest Idaho. *Forest Prod. J*. 54(2):21–27.

Harrill, H. and H.-S. Han. 2012. Productivity and cost of integrated harvesting of wood chips and sawlogs in stand conversion operations. *Int. J. Forestry Res*. 2012:1–10. DOI:10.1155/2012/893079

Hartley, D. S., D. N. Thompson, and H. Cai. 2021. Woody feedstock 2020 state of technology report. US Department of Energy, Office of Scientific and Technical Information. DOI:10.2172/1782211

Haywood, J. D. 2005. Influence of precommercial thinning and fertilization on total stem volume and lower stem form of loblolly pine. *South. J. Appl. Forestry* 29(4):215–220. DOI:10.1093/sjaf/29.4.215

Hernández, G. A., R. A. Harper, and D. B. South. 2016. Tree planting in the South, 1925 to 2012. *Tree Planter's Notes* 59:4–8.

Hillring, B. 2006. World trade in forest products and wood fuel. *Biomass and Bioenergy* 30(10):815–825. DOI:10.1016/j.biombioe.2006.04.002

International Energy Agency (IEA). 2020. World Energy Balances 2020 (database). https://www.iea.org/reports/sustainable-bioenergy-for-georgia-a-roadmap. Accessed September 20, 2021.

Jernigan, P., T. Gallagher, J. Aulakh, R. Tufts, and T. McDonald. 2013. Implementing residue chippers on harvesting operations in the southeastern US for biomass recovery. *Int. J. Forest Eng*. 24:129–136.

Johnson, T., J. Bentley, and M. Howell. 2008. The South's timber industry—An assessment of timber product output and use, 2005. US Department of Agriculture, Forest Service Resource Bulletin SRS-135. U.S. Department of Agriculture Forest Service, Southern Research Station, Asheville, North Carolina.

Joudrey, J., W. McDow, T. Smith, and B. Larson. 2012. European Power from U.S. Forests: How Evolving EU Policy is Shaping the Transatlantic Trade in Wood Biomass. Environmental Defense Fund, New York, New York.

Kizha, A., H.-S. Han, T. Montgomery, and A. Hohl. 2015. Biomass power plant feedstock procurement: Modeling transportation cost zones and the potential for competition. *Calif. Agric. J*. 69(3):184–190.

Kohavi, R. 1995. A study of cross-validation and bootstrap for accuracy estimation and model selection. Proceedings of the Fourteenth International Joint Conference on Artificial Intelligence; August 20–25, 1995; Montreal, Quebec, Canada. https://www.ijcai.org/Proceedings/95-2/Papers/016.pdf. Accessed October 20, 2021.

Koirala, A., A. R. Kizha, and S. Baral. 2017. Modeling height-diameter relationship and volume of Teak (Tectona grandis L. F.) in central lowlands of Nepal. *J. Trop. Forestry Environ*. 7(1):28–42. DOI:10.31357/jtfe.v7i1.3020

Kumarappan, S., S. Joshi, and H. L. MacLean. 2009. Biomass supply for biofuel production: Estimates for the United States and Canada. *BioResources* 4(3):1070–1087. DOI:10.15376/biores.4.3.1070-1087

Kwak, S. G. and J. H. Kim. 2017. Central limit theorem: The cornerstone of modern statistics. *Korean J. Anesthesiol*. 70(2):144–156.

Leinonen, A. 2004. Harvesting technology of forest residues for fuel in the USA and Finland. *VTT Tiedotteita - Valtion Teknillinen Tutkimuskeskus* 2229:3–132.

Liski, E., P. Jounela, H. Korpunen, A. Sosa, O. Lindroos, and P. Jylhä. 2020. Modeling the productivity of mechanized CTL harvesting with statistical machine learning methods. *Int. J. Forest Eng*. 31(3) :253–262. DOI:10.1080/14942119.2020.1820750

Louisiana: Public Law Louisiana Act 84. 2020. https://www.legis.la.gov/legis/BillInfo.aspx?s=20rs&b=HB442. Accessed September 20, 2021.

McDonald, T. P., S. E. Taylor, R. B. Rummer, and J. Valenzuela. 2001. Information needs for increasing log transport efficiency. First International Precision Forestry Symposium, 12 pp. https://www.srs.fs.usda.gov/pubs/ja/ja_mcdonald012.pdf. Accessed October 20, 2021.

Mcgregor, K. F., M. S. Watt, P. E. Hulme, and R. P. Duncan. 2012. What determines pine naturalization: Species traits, climate suitability or forestry use? *Divers. Distrib*. 18(10):1013–1023. DOI:10.1111/j.1472-4642.2012.00942.x

McKeand, S., T. Mullin, T. Byram, and T. White. 2003. Deployment of genetically improved loblolly and slash pines in the south. *J. Forestry* 101(3):32–37. DOI:10.1093/jof/101.3.32

Moskalik, T. and A. Gendek. 2019. Production of chips from logging residues and their quality for energy: A review of European literature. *Forests* 10(3):262. DOI:10.3390/f10030262

Nebeker, T. E., D. J. Hodges, K. B. Karr, and M. D. Moehring. 1985. Thinning practices in southern pines—With pest management recommendations. Technical Bulletin 1703. US Department of Agriculture, Forest Service. https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwj-1-qD_tnzAhVjmWoFHSuBAwEQFnoECAQQAQ&url=https%3A%2F%2Fageconsearch.umn.edu%2Frecord%2F156818%2Ffiles%2Ftb1703.pdf&usg=AOvVaw2kFEqH7ZT-aaQIPuHnCdO5. Accessed October 20, 2021.

Nesbit, T. S., J. R. R. Alavalapati, P. Dwivedi, and M. V. Marinescu. 2011. Economics of ethanol production using feedstock from slash pine (Pinus elliotti) plantations in the southern United States. *South. J. Appl. Forestry* 35(2):61–66.

Nickens, E. T. 2014. Why U.S. forests are fueling Europe. *Audubon, Nat. Audubon Soc*. September–October 2014. https://www.audubon.org/magazine/september-october-2014/why-us-forests-are-fueling-europe. Accessed October 20, 2021.

North Carolina: Public Law North Carolina Session Law 2012-78. 2012. https://www.ncleg.gov/EnactedLegislation/SessionLaws/PDF/2011-2012/SL2012-78.pdf. Accessed September 20, 2021.

Nowak, J. 2004. Southern pine beetle prevention and restoration. *Forest Landowners Conf. Proc*. *63:*21–22.

Nowak, J., C. Asaro, K. Klepzig, and R. Billings. 2008. The southern pine beetle prevention initiative: Working for healthier forests. *J. Forestry* 106(5):261–267. DOI:10.1093/jof/106.5.261

Nowak, J., J. R. Meeker, D. R. Coyle, C. A. Steiner, and C. Brownie. 2015. Southern pine beetle infestations in relation to forest stand conditions, previous thinning, and prescribed burning: Evaluation of the southern pine beetle prevention program. *J. Forestry* 113(5):454–462. DOI:10.5849/jof.15-002

Pan, F., H.-S. Han, L. R. Johnson, and W. J. Elliot. 2007. Production and cost of harvesting and transporting small-diameter trees for energy. International Mountain Logging and 13th Pacific Northwest Skyline Symposium, J. Sessions and Y. Havill (Eds.), April 1–6, 2007, Corvallis, Oregon. Sponsored by Department of Forest Engineering, Oregon State University, and International Union of Forest Research Organizations. pp. 215–225. https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwiw6cHWn9rzAhXMnGoFHaB-D6wQFnoECAIQAQ&url=https%3A%2F%2Fwww.iufro.org%2Fdownload%2Ffile%2F4702%2F4504%2F30000-mountain-logging-symp07_p_pdf%2F&usg=AOvVaw0WhYnMj7lyiTfn8mmdIAVO. Accessed October 20, 2021.

Peksa, M., P. Dolzan, A. Grassi, J. Heinimo, M. Junginger, T. Ranta, and A. Walter. 2007. Global wood pellets markets and industry: Policy drivers, market status and raw material potential. *IEA Bioenergy Task* 40:5, 120.

Perlack, R. D., L. L. Wright, A. F. Turhollow, R. L. Graham, B. J. Stokes, and D. C. Erbach. 2005. Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply. Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Pokharel, R., R. K. Grala, D. L. Grebner, and W. H. Cooke. 2019. Mill willingness to use logging residues to produce electricity: A spatial logistic regression approach. *Forest Sci*. 65(3):277–288. DOI:10.1093/forsci/fxy061

Prestemon, J., J. Pye, J. Barbour, G. R. Smith, P. Ince, C. Steppleton, and W. Xu. 2010. U.S. wood-using mill locations - 2005. *US Department of Agriculture, Forest Service, Southern Research Station, Asheville, North Carolina*. https://www.srs.fs.usda.gov/econ/data/mills/. Accessed October 20, 2021.

Primary Forest Products Network. https://primary.forestproductslocator.org/. Accessed September 1, 2021.

R Core Team. 2019. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/. Accessed October 20, 2020.

Rankin, W. and N. Herbert. 2014. Restoration in the southern Appalachians: A dialogue among scientists, planners, and land managers. General Technical Report SRS-GTR-189. US Department of Agriculture-Forest Service, Southern Research Station, Asheville, North Carolina. pp. 1–48.

Richardson, J. 2006. Sustainable production systems for bioenergy: Impacts on forest resources and utilization of wood for energy. *Biomass and Bioenergy* 30:279–384.

Schultz, R. P. 1997. Loblolly pine: The Ecology and Culture of the Loblolly Pine (Pinus taeda L.). Agriculture Handbook 713. US Government Printing Office, Washington, D.C.

Schultz, R. P. 1999. Loblolly—The pine for the twenty-first century. *New Forests* 17(1–3): 71–88.

Shabani, N., S. Akhtari, and T. Sowlati. 2013. Value chain optimization of forest biomass for bioenergy production: A review. *Renew. Sustain. Energy Rev*. *23:* 299–311. DOI:10.1016/j.rser.2013.03.005

Smidt, M. F., Y. Zhang, and B. Zheng. 2012. Financial assessment of logging residue collection in the southeast United States. *Forest Prod. J*. 62:10–17.

Smith, B. W., P. D. Miles, J. S. Vissage, and S. A. Pugh. 2004. Forest resources of the United States, 2002. General Technical Report NC-241. US Department of Agriculture, Forest Service, North Central Forest Experiment Station, St. Paul, Minnesota. DOI:10.2737/NC-GTR-241

Smith, B. W., J. S. Vissage, D. R. Darr, and R. M. Sheffield. 2001. Forest resources of the United States, 1997. General Technical Report NS-219. US Department of Agriculture, Forest Service, North Carolina Central Research Station, Asheville, North Carolina.

South Carolina Code of Laws. 2021. Title 56 Chapter 5. https://www.scstatehouse.gov/code/t56c005.php. Accessed September 20, 2021.

South, D. B. and R. A. Harper. 2016. A decline in timberland continues for several southern yellow pines. *Forest Ecol*. 114(March):116–124.

Spelter, H. and D. Toth. 2009. North America's wood pellet sector. Research Paper FPL-RP-656. US Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, Wisconsin.

Stephens, S. L., B. M. Collins, C. J. Fettig, M. A. Finney, C. M. Hoffman, E. E. Knapp, M. P. North, H. Safford, and R. B. Wayman. 2018. Drought, tree mortality, and wildfire in forests adapted to frequent fire. *BioScience* 68(2):77–88. DOI:10.1093/biosci/bix146

Stokes, B. J. 1998. Harvesting systems for multiple products—An update for the United States. *In:* IEA Bioenergy Wood Fuels from Conventional Forestry; Proceedings of the Third Annual Workshop of Activity 1.2 (Harvesting) / Task XII / IEA Bioenergy; P. Hakkila, M. Heino, and E. Puranen (Eds.); October 18, 1997; Jasper, Alberta, Canada. The Finnish Forest Research Institute, Helsinki, Finland. pp. 49–56. https://www.srs.fs.usda.gov/pubs/ja/ja_stokes012.pdf. Accessed Oct 20, 2021.

Stokes, Watson, W. F. and D. L. Sirois. 1987. Factors affecting power requirements for chipping whole trees. ASAE Paper 87-6012. American Society of Agricultural Engineers, St. Joseph, Michigan.

Susaeta, A., J. Alavalapati, P. Lal, J. R. Matta, and E. Merce. 2010. Assessing public preferences for forest biomass based energy in the southern United States. *Environ. Manag*. 45(4):697–710. DOI:10.1007/s00267-010-9445-y

TimberMart-South. 2010. Norris Foundation, Athens, Georgia: 1st quarter. http://www.timbermart-south.com/. Accessed May 12, 2020.

TimberMart-South. 2020. Norris Foundation, Athens, Georgia: 1st quarter. http://www.timbermart-south.com/. Accessed May 12, 2020.

Virginia: Public Law Virginia House Bill 2072. 2015. https://lis.virginia.gov/cgi-bin/legp604.exe?151+sum+HB2072. Accessed September 20, 2021.

Voegele, E. 2021. USDA: US wood pellet exports at 556,802 metric tons in February. *Biomass Mag.* http://biomassmagazine.com/articles/

17860/usda-us-wood-pellet-exports-at-556-802-metric-tons-in-february. Accessed October 20, 2021.

Vogt, K. A., M. G. Andreu, D. J. Vogt, and R. Sigurdardottir. 2005. Societal values and economic return added for forest owners by linking forests to bioenergy production. *J. Forestry* 103:21–27.

Wakeley, P. C. 1954. Planting the Southern Pines. US Department of Agriculture, Agriculture Monograph No. 18, Washington, D.C.

Waldron, J. D. 2011. Forest restoration following southern pine beetle. *In:* Southern Pine Beetle II. General Technical Report SRS-140. R. N. Coulson and K. D. Klepzig (Eds.). US Department of Agriculture Forest Service, Southern Research Station, Asheville, North Carolina. pp. 353–363, 140, 353–363.

Wear, D. N. and J. G. Greis. 2012. The southern forest futures project: Summary report. General Technical Report SRS-GTR-168. US Department of Agriculture, Forest Service, Southern Research Station, Asheville, North Carolina.

Westbrook, M. D., W. D. Greene, and R. L. Izlar. 2007. Utilizing forest biomass by adding a small chipper to a tree-length southern pine harvesting operation. *South. J. Appl. Forestry 31*(4):165–169. DOI:10.1093/sjaf/31.4.165

Withycombe, R. P. 1982. Estimating costs of collecting and transporting forest residues in the northern Rocky Mountain Region. General Technical Report INT-81. US Department of Agriculture, Forest Service, Intermountain Forest and Range, Ogden, Utah.

Xi, W., J. D. Waldron, D. M. Cairns, C. W. Lafon, A. G. Birt, M. D. Tchakerian, K. D. Klepzig, and R. N. Coulson. 2012. Restoration of southern pine forests after the southern pine beetle. *In:* A Goal-Oriented Approach to Forest Landscape Restoration. Springer, Dordrecht, The Netherlands. pp. 321–354. https://doi.org/10.1007/978-94-007-5338-9_12. Accessed October 20, 2021.