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Availability of Logging Residues and Likelihood of Their Utilization for Electricity Production in the US South

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Abstract

This study estimated quantities of logging residues that can physically be recovered from harvest sites and utilized for electricity production in the US South. Because of a small number of mills utilizing logging residues, this study determined their willingness to utilize additional logging residues to produce electricity as a function of woody residue utilization characteristics of a mill and mill management's attitudes toward factors limiting utilization of this feedstock. Approximately 98 percent of logging residues occur within a 35-mile hauling distance from mills. Although almost all physically available logging residues could be recovered with a relatively short hauling distance, a mail survey indicated that only 4 percent of mills utilized this feedstock. Willingness to utilize additional logging residues to produce electricity by mill management was positively associated with the quantity of woody residues already used and anticipated equipment upgrades to facilitate electricity production, whereas it was negatively related with the quantity of generated mill residues. Mill management that considered a lack of storage space an important limitation was less likely to utilize additional logging residues. Increased utilization of logging residues for electricity production will be contingent on the implementation of bioenergy favorable policies and availability of technical and financial assistance to mills.

Keywords: bioenergy, biomass, equipment upgrades, hauling distance, woody residues utilization

Renewable energy sources such as woody biomass have gained substantial attention because of increasing concerns over fossil fuel usage, carbon dioxide (CO_2) emissions, and climate change (Nepal et al. 2015). Logging residues are a type of woody biomass feedstock that consists of a woody material left after logging operations because it was deemed commercially unfit for primary wood products such as lumber, veneer, or poles

Management and Policy Implications

Most logging residues in the southern United States occur within a 35-mile hauling distance from existing milling facilities. Despite the fact that utilization at this distance is economically feasible, the usage of logging residues remains low. Increased usage can be achieved if a greater number of mill managers are willing to consider logging residues as a feedstock for bioelectricity. Increased utilization of logging residues to produce electricity will require an increase in the capacity to process logging residues at mills, equipment upgrades to facilitate electricity production, and additional storage space. Although more than two third of mills considered high transportation costs and lack of equipment to handle logging residues as factors limiting additional utilization, we found these factors to be insignificant in defining their willingness to utilize. Mill management considers them immutable limits and thus not part of their decisionmaking process. It will be necessary to demonstrate that these limitations can be overcome for additional utilization of logging residues. Strategies and policies aimed at increasing the utilization of woody residues will, therefore, need to incorporate local-, state-, and federal-level support mechanisms for technical upgrades of mill infrastructure. Financial assistance in the form of investment subsidies and low-interest loans to purchase equipment required to handle, transport, and process logging residues, and financial incentives such as bioenergy production credits, tax breaks, and contracted energy buyback guarantees might be needed to increase the competitiveness of logging residues as a bioenergy feedstock.

(Nurmi 2007, Pokharel et al. 2017a). Although logging residues are often left at the harvest sites to provide nutrients for natural regeneration (Evans 2017), using logging residues instead of agricultural feedstocks will lower environmental impacts and the cost of biofuel production (Daystar et al. 2013). Although excessive removal of logging residues is potentially associated with negative environmental impacts such as soil nutrient depletion and the potential for soil compaction, a moderate removal (30–70 percent, depending on forest site quality) does not affect nutrient availability (Börjesson 2000, DOE 2011). Furthermore, using logging residues provides additional environmental benefits such as the reduction in wildfire hazard and improvement in forest health (Evans 2017). Thus, sustainable utilization of logging residues for bioenergy purposes can potentially not only provide numerous environmental benefits but also improve the economic viability of timber production.

Gan and Smith (2006) estimated that 36.20 million dry tons (dt) of logging residues were typically left in forests after harvesting operations in the United States. They concluded that utilizing this feedstock had the potential of producing 67.50 terawatt hours of electricity. Furthermore, it was estimated that 47.00 million dt per year of logging residues were potentially available from forests at a roadside price of US$40/dt or less (DOE 2016). However, high procurement costs have limited utilization of logging residues. Several studies have reported ranges of cost associated with logging residues procurement. Grushecky et al. (2007) reported that, depending upon different extraction and trucking costs, the delivered price of pine logging residues in West Virginia ranged from US$33.45/dt to US$110.97/dt (US$58.20–193.10 per hundred cubic feet) when hauled for 123 miles. In Montana, approximately 28 percent of the delivered biomass was financially available for procurement at US$31.52/dt (Jones et al. 2013). Pokharel et al. (2017a) stated that managers and owners of primary forest product manufacturers (mills) in the southern United States were willing to pay US$11.92 per green ton (gt) (US$23.84/dt; assuming a 50 percent moisture content) for delivered logging residues. Despite their physical availability, logging residues have not been utilized for electricity production to the extent that other woody feedstocks (e.g., biomass crops, mills residues) have had. Only 4 percent of mills used logging residues, and they constituted only 4 percent of all their feedstocks by green weight (Pokharel et al. 2017a, b). Such low utilization levels, despite physical availability, warrant further investigation of mill manager and owner opinions on the economic viability of logging residues utilization and factors potentially limiting their usage.

Harvesting and transportation costs accounted for two-thirds of the total cost of energy production from logging residues (Perez-Verdin et al. 2009, DOE 2016). Hence, the hauling distance between harvest sites and a mill is one of the major factors affecting the cost of procuring logging residues. Additionally, the feasibility of procurement depends on the availability and quality of transportation infrastructure and access to logging residue piles, as these factors determine the total cost of logging residues recovery (Zamora-Cristales et al.

2013, Berry and Sessions 2017). To ensure the sustainable and profitable supply and utilization of logging residues, a reduction in transportation costs and haul time is necessary (Alam et al. 2012). Therefore, it is essential to consider and incorporate the impact of hauling distance in estimating the economic feasibility of the logging residues for electricity production.

On the other hand, mill management's willingness to utilize logging residues is as crucial as improving supply-chain efficiency that reduces transportation costs. Pokharel et al. (2017a, b) studied mill-management opinions on the possibility of enhancing woody residues utilization in the southern United States. Mills utilized larger quantities of woody residues if they had larger processing capacities, implemented equipment upgrades to facilitate electricity production, and incurred lower transportation costs for acquiring logging residues. Also, mills were more likely to utilize additional logging residues if they were close to a major road and other sawmills; pulp, paper, and paperboard mills; and post mills (Pokharel et al. 2019). Additionally, there were only a few mills with a processing capacity large enough to utilize woody residues for bioenergy (heat, electricity, and others) production, which also limited utilization of logging residues (Pokharel et al. 2017b). Studies by Pokharel et al. (2017a, b) were mainly focused on the usage of woody residues, primarily consisting of mill and logging residues, for bioenergy production including electricity, heat, and chemicals. Pokharel et al. (2019) investigated the impact of the proximity of mills with other mills, cities, forests, and transportation infrastructure on mill willingness to utilize logging residues and did not study the impact of haul distances on availability of logging residues and the mill management's attitudes related to factors limiting utilization of additional logging residues.

The present study offers an analysis of potential logging residue utilization for electricity production in the southern United States designed to bridge the gap between logistics and econometric studies. In doing so, it recognizes that whereas logistics and the underlying utilization costs define the geographic area of residue supply, cost alone is not enough to determine whether residue use will be adopted with that area. First, we employ a spatial database of regional mills and the existing road networks to outline their procurement areas across a range of hauling distances. When combined with county-level logging residue availability, this provides a proxy of the quantity of logging residues available at different price levels. Next, we evaluate mill owner and manager willingness to utilize additional logging residues to produce electricity as a function of a mill's woody residue utilization characteristics and factors limiting the utilization of additional logging residues. The paper continues with a description of data, methods, and results, and follows with a discussion that recommends two specific actions likely to stimulate logging residue utilization for bioelectricity: processing capacity improvements and the development of policy that would facilitate the involvement of more mills in the utilization process.

Methods

Study Area

The study area encompasses 12 states in the southern United States: Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, Oklahoma, South Carolina, Tennessee, and Virginia (Figure 1). The region is also called the wood basket of the United States because it produces half of the nation's forest products and has proportionally large quantities of logging residues (Oswalt and Smith 2014). Previous studies indicated that 16.50 million dt of logging residues were potentially available for recovery from harvest sites in the region (Gan and Smith 2006). Approximately 50 percent of the land in the southern United States is covered by forests (Oswalt and Smith 2014). In 2011, the forest products industry in the southern United States employed 470,000 individuals and produced a gross output valued at US$133 billion (Dahal et al. 2015). Additionally, the region has multiple mill clusters (Hagadone and Grala 2012) with a supply chain suitable for recovery of traditional wood products (Gonzalez et al. 2011) and woody biomass feedstocks for biofuel and bioenergy conversion (Conrad et al. 2011, Poudel et al. 2016).

Data

Data on physical locations of 1,324 mills were obtained as a geo-referenced shapefile from Latta et al. (2018). The mill list included sawmills; plywood and veneer producers; mechanical and chemical pulp producers; panel, oriented strand board, medium-density fiberboard, and other panel and composite board manufacturers; and biopower and pellet producers (Figure 2). The mill list did not include chipping, paper, and cofiring facilities that were included in USDA Forest Service mill data by Prestemon et al. (2010). We updated the Latta et al. (2018) database using paid and free sources that included the Fastmarkets RISI mill asset database, Forisk

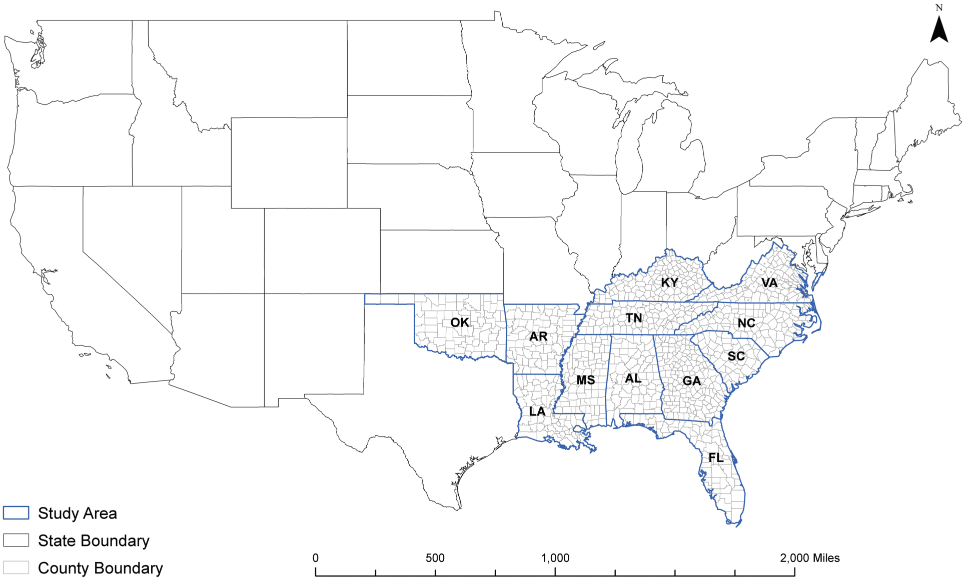

Figure 1. Location of the study area in the United States.

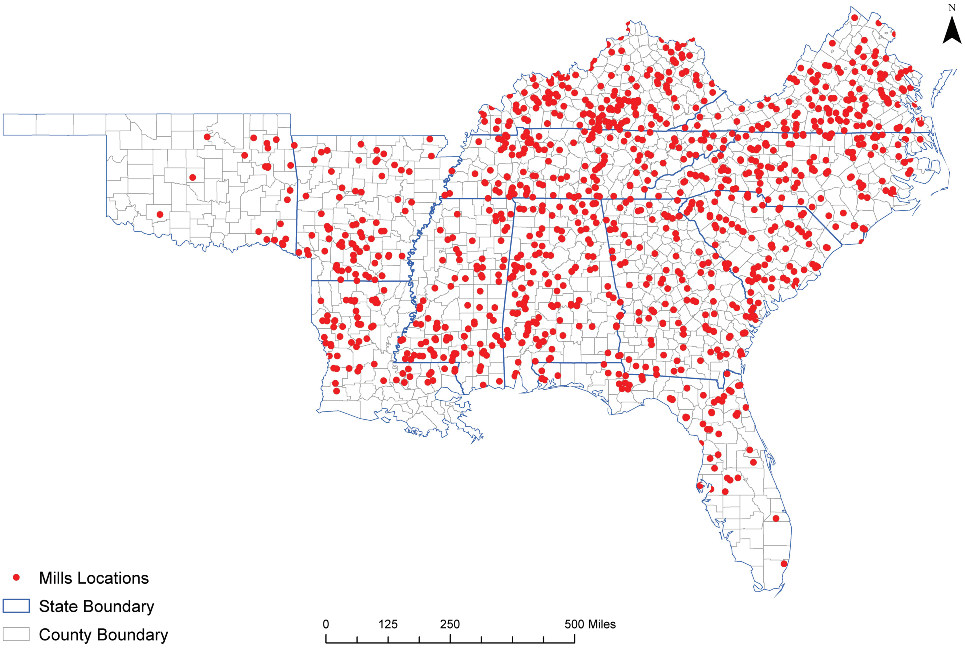

Figure 2. Distribution of forest products processing facilities (mills) in the southern United States.

Consulting, and corporate annual reports and websites. The latest update was done in 2018 and included 1,324 mills in the study area of 3,340 mills across the continental United States. For this study, an additional 896 mills outside the study area were included in the analysis because logging residues from the study area can be hauled to these mill locations and utilized for electricity production. Data related to existing road networks were obtained as a layer package and included locations of interstate and state highways, county roads, limited access roads, minor roads, city streets, junctions, ferries, and other roads such as four-wheel drive roads, excluding private forest roads (Figure 3, ESRI 2018). Estimates of logging residue quantities available in each state's county were obtained as a shapefile from National Renewable Energy Laboratory's Biopower Atlas (Figure 4, NREL 2012). Data related to mill characteristics of woody residues utilization (including mill and logging residues), procurement characteristics (price paid for logging residues at the gate, actual hauling distances, and economically feasible hauling distances), and mill management's actions and opinions toward

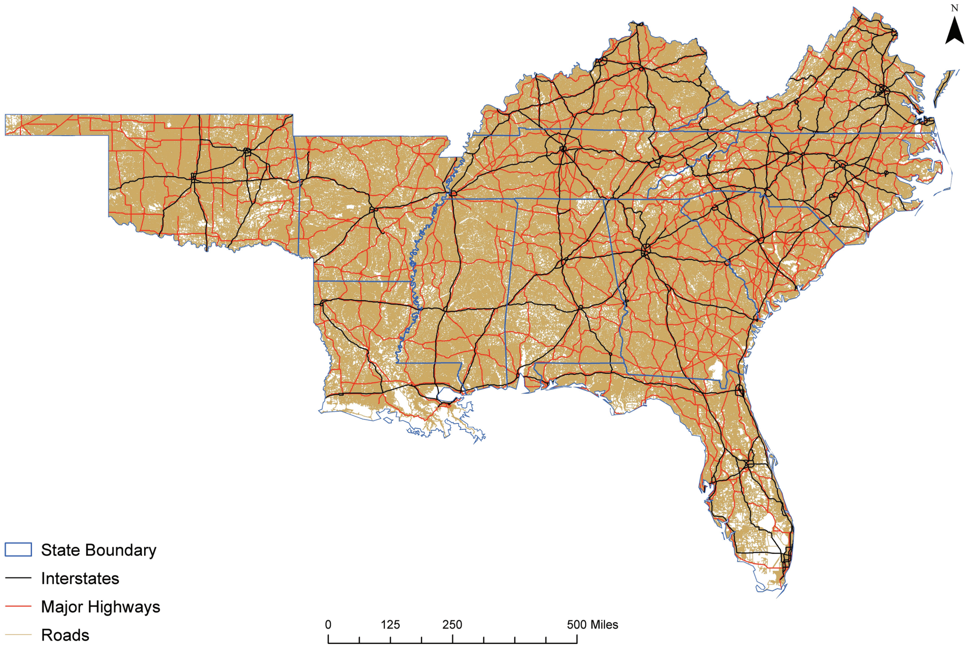

Figure 3. Distribution of transportation networks in the southern United States (input data source: ESRI 2018).

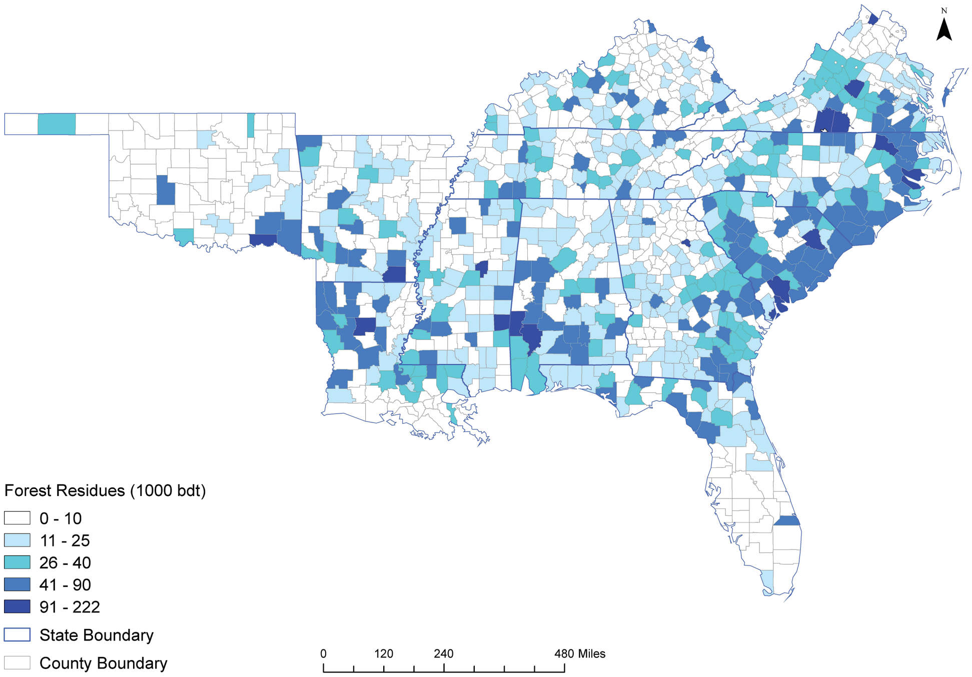

Figure 4. Physical quantities of logging residues available in the southern United States based on input data obtained from National Renewable Energy Laboratory's (NREL) Biopower Atlas (NREL 2012).

factors limiting utilization of additional quantities of logging residues were collected using a census survey of mills in the southern United States. The survey was sent to 2,138 forest products manufacturers reported in the mill list by Prestemon et al. (2010) for the southern United States utilizing Dillman's Tailored Design Method and involved four mailings (Dillman et al. 2009). The mill survey was carried out in 2012, and a more recent survey could better represent current opinions of mill owners and managers toward utilization of logging residues. However, all new growth in bioenergy production was facilitated through the construction of new pellet facilities that mostly used clean chips and not logging residues (Goh et al. 2013, Singh et al. 2016).

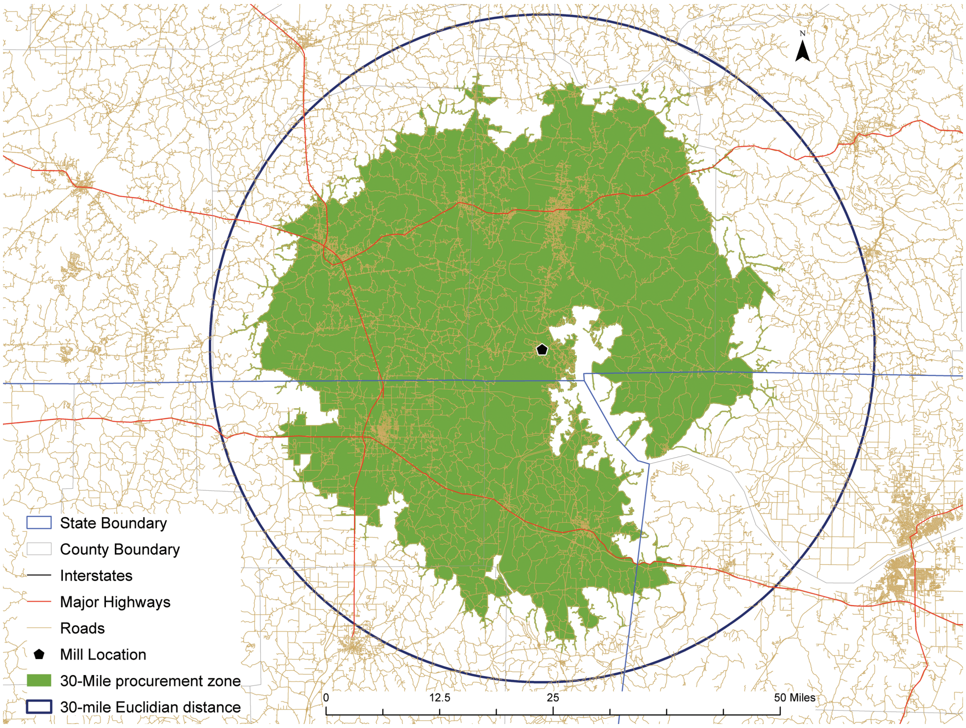

Figure 5. Example of a 30-mile procurement area around a mill identified based on existing transportation network (the irregular shape) and the Euclidean distance (the circle).

The analysis on the utilization of additional quantities of logging residues for electricity production at the mills still provides useful insight into mill-management willingness to use logging residues for bioenergy purposes.

Estimates of Logging Residues Available for Procurement

A polygon representing the procurement area for each mill was generated, and it outlined an area where forest commodities such as logging residues are hauled from a specified distance using existing transportation networks as shown in Figure 5. The procurement area around each mill was mapped using ArcGIS 10.5 Network Analyst. The mapped procurement zone had an irregular shape because it was based on an actual hauling distance using existing roads rather than an arbitrary straight line (Euclidean distance). An initial hauling distance of 5-miles was selected because it was the shortest hauling distance reported by the mills participating in the survey. In the next step, individual mill procurement zones were merged into a single polygon representing an aggregated procurement zone for all mills in the region to avoid double counting where procurement zones overlapped each other. The process was repeated to estimate aggregated procurement zones for 10-, 15-, 20-, 25-, 30-, 35-, 40-, 45-, 50-, 55-, and 60-mile hauling distances. All forest materials, including logging residues inside these procurement zones, were considered available for hauling and utilization in the mills. This study assumed that if trucks could reach the forest edge, logging residues were readily available for pick-up and transportation.

The physical quantities of logging residues available annually within a procurement zone were estimated based on a proportion of a county's forest area located within a respective procurement zone to the total forested land area in that county. It was assumed that logging residues were uniformly distributed across the forest, and the proportion of the procurement area to its respective forest area in a county represented a percentage of logging residues physically available for extraction within the county. For example, if a procurement zone covered 50 percent of a forest area of a county, it was assumed that 50 percent of logging residues were physically available for recovery in that county. Results were aggregated at the state level.

Statistical Analysis

A nonresponse bias test was implemented to determine whether survey responses were representative of all mills in the southern United States by conducting a paired *t*-test and comparing responses between: (a) first and last 50 returned questionnaires, (b) proportions of surveys sent to and returned from each state, and (c) proportions of surveys sent to and returned from each mill type. Additionally, a comparative analysis was employed between mill management willing and not willing to utilize additional logging residues to produce electricity to determine differences in mill characteristics related to woody residues utilization, procurement characteristics, and mill-management opinions toward factors limiting usage of additional logging residues. Finally, a regression model was constructed to determine the probability that mill management would be willing to utilize additional logging residues for electricity production based on mill characteristics of woody residues utilization, and mill-management opinions toward factors limiting logging residue utilization.

An empirical model was constructed where the observed probability of mill management's willingness to utilize additional logging residues to produce electricity was represented as a function of a binary choice. A binary logit regression was preferred over a linear probability model (LPM) because probability in the LPM is not bounded and can exceed 1, whereas the properties of variance and error remain unchanged (Greene 2008), allowing for a test of errors to be carried on LPM and then extended to a logit model as specified in Equation 1.

$$\text{Logit}\ (P(y_i = 1)) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_n x_n + \varepsilon \quad (1)$$

where: $P(y_i = 1)$ is the probability that a mill management would be willing to utilize additional quantities of logging residues to produce electricity, y is a dependent variable representing a binary response of whether a mill management would be willing ($y = 1$) or not willing ($y = 0$) to utilize additional quantities of logging residues to produce electricity (WILLING), $x_i$represents a set of independent variables representing mill characteristics of woody residues utilization and mill managers' opinions toward factors limiting utilization of additional logging residues, β_i denotes the parameter estimates, and ε is the error. Unlike in the LPM, coefficients of the logit model do not provide direct interpretation; therefore, the sample average estimates of marginal effects ($\mathrm{d}[\text{Logit}\ (P(y_i = 1))]\ /\mathrm{d}x_i$) of independent variables were estimated, as specified in Equation 2, to provide inferences similar to coefficients in LPM (Greene 2008).

$$\frac{\mathrm{d}\ [\text{Logit}(P(y_i = 1))]}{\mathrm{d}x_i} = b_i \frac{\exp(b_0 + b_1\bar{x}_1 + b_2\bar{x}_2 = \ldots + b_n\bar{x}_n)}{(1 + \exp(b_0 + b_1\bar{x}_1 + b_2\bar{x}_2 = \ldots + \ b_n\bar{x}_n))^2} \quad (2)$$

where $\bar{x}_i$ represents the average of the independent variable and b_i denotes the parameter estimates from Equation 1. Tests for heteroscedasticity, multicollinearity, endogeneity, and serial autocorrelations were also carried out to ensure that derived estimators were the best linear unbiased estimator of the coefficients. All the tests were carried out in the LPM.

Variable Construction and Model Specification

The current level of woody residues utilization in a mill to produce bioenergy has been reported as one of the important factors associated with mill management's willingness to utilize additional logging residues (Pokharel et al. 2017a). A high rate of mill residue utilization for bioenergy and other purposes (mulching, landscaping, etc.) and equipment upgrades implemented to increase mill processing capacity and efficiency (DOE 2016) most likely will result in increased demand for alternative feedstocks, such as logging residues, which will necessitate specialized equipment upgrades to collect, transport, and utilize logging residues to produce electricity (Johnson et al. 2012, Yue et al. 2014). The need for additional specialized equipment may increase the cost of procuring logging residues and discourage mills from utilizing this feedstock. Similarly, anticipated future equipment upgrades to facilitate the production of electricity will likely increase willingness to utilize additional logging residues (Pokharel et al. 2017a, b).

It has been difficult and costly to transport and utilize logging residues because of high transportation costs and lack of appropriate equipment to collect, load, store, and process logging residues (Pokharel et al. 2017a). Almost two-thirds of the cost of using logging residues for bioenergy can be attributed to procurement (Perez-Verdin et al. 2009, DOE 2016). Reduction in transportation cost and haul time can increase the profitability of supply and utilization of woody biomass feedstocks such as logging residues (Alam et al. 2012). Although transporting dry logging residues can reduce haul cost, logging residues in the southern United States are brought to the mills without drying, and logging operators are paid per green weight. Additionally, drying requires sophisticated heating equipment and storage space at a forest landing or a mill, depending on where drying and storage are done (Nurmi 1999). Lack of space to store logging residues and equipment to dry them could limit their utilization. Also, lack of equipment to handle logging residues at the harvest site as well as at mills could limit their utilization because efficient and suitable equipment to collect and process logging residues is needed to reduce the cost of procuring logging residues (Smidt et al. 2012). Above all, to increase utilization of logging residues, they must be physically available, whereas mills must have sufficient processing capacity to utilize them. Therefore, the current level of woody residue utilization (UTILIZE) and quantity of disposable residues produced at a mill (DISPOSE) were continuous variables used in determining mill willingness to utilize logging residues. Anticipated upgrades facilitating electricity production (UPGRADE) were a binary variable. The importance of high transportation costs (TCOST), importance of lack of storage space at a mill (STORE), importance of lack of equipment to handle logging residues at a mill (EQUIP), importance of availability of logging residues (RESID), importance of limited mill capacity to process logging residues (MILLCAP), and importance of other limiting factors (OTHER) were identified as important factors that will help increase understanding of mill behavior in regard to future utilization of additional logging residues for electricity (Table 1). The factors were reported by mill management and measured on a Likert scale of 1–5, where 1 is not important, and 5 is most important. Equation 3 represents a model specification for a regression analysis to estimate the association of the probability that mill management would be willing to utilize additional logging residues with the aforementioned factors.

$$\begin{aligned} \mathrm{WILLING} = f(&\mathrm{UTILIZE},\ \mathrm{DISPOSE},\ \mathrm{UPGRADE},\\ &\mathrm{TCOST},\ \mathrm{STORE},\ \mathrm{EQUIP},\ \mathrm{RESID},\\ &\mathrm{MILLCAP},\ \mathrm{OTHER}) \end{aligned} \tag{3}$$

This study did not use the price of delivered logging residues and hauling distances reported by the mill management in the regression model because of the relatively low number of observations. The actual transportation cost was also not available because logging residues were paid for at the gate, and the payment included collection and transportation costs. Although 34 mills reported gate prices for logging residues, and 68 reported economic hauling distances for logging residues, the regression model could utilize only 14 observations because mill managers reporting gate price or hauling distance did not report other mill characteristics and vice versa. To address this limitation and better understand the effect of procurement costs on logging residue utilization, this study estimated forest area with a total quantity of logging residues physically available for recovery at different hauling distances from a mill.

Results

Quantities of Logging Residues Physically Available for Procurement

Figure 6 presents the procurement zones for 5-, 10-, 15-, 20-, 25-, 30-, 35-, 40-, 45-, 50- 55-, and 60-mile hauling distances. The estimates of logging residues' physical availability at these hauling distances are presented in Table 2. Annual quantities of logging residues physically available for procurement varied by hauling distance and state. On average, mills in the southern United States would potentially be able to recover 10 percent [2.23 million bone dry tons (bdt)] of available logging residues within a 5-mile, 59 percent (13.58 million bdt) within a 15-mile, 90 percent (20.82 million bdt) within a 25-mile, 98 percent (22.66 million bdt) within a 35-mile, 99 percent (23.03 million bdt) within a 45-mile, and 100 percent within a 60-mile procurement zone annually.

Virginia, North Carolina, and Georgia had the largest quantities of logging residues available within a 15-mile hauling distance at 1.79, 1.77, and 1.49 million bdt, respectively. In terms of the proportion of potentially recoverable logging residues with a 15-mile hauling distance, Kentucky had the highest level at 77 percent (1.24 million bdt), followed by Virginia at 70 percent (1.79 million bdt), and Tennessee at 68 percent (0.88 million bdt). Oklahoma and Florida had the smallest levels of potentially extractable logging residues corresponding to 33 percent (0.07 million bdt) and 46 percent (0.57 million bdt), respectively. At a 25-mile hauling distance, Kentucky would be able to recover 97 percent of available logging residues (1.57 million bdt). Similarly, Virginia, Tennessee, South Carolina, Mississippi, North Carolina, and Georgia could potentially recover 96 percent (2.45 million bdt), 92 percent (1.19 million bdt), 92 percent (2.12 million bdt), 91 percent (1.63 million bdt), 91 percent (2.69 million bdt), and 90 percent (2.51 million bdt) of available logging residues, respectively. When a hauling distance was increased to 35 miles, most states would be able to recover all available logging residues, well above 90 percent, except Oklahoma. For example, Kentucky, Virginia, and South Carolina would be able to recover 100 percent of their logging residues, which corresponded

Table 1. Variables and descriptive statistics derived from the census mail survey of mills in the southern United States conducted in 2012 to determine their willingness to utilize additional logging residues for electricity production.

Variable	Variable descriptions	*N*	Mean	SD	Median	Max
Woody residue utilization characteristics of a mill						
WILLING	Mill willingness to utilize additional logging residues to produce electricity. A binary variable: 1 if willing, 0 if not.	227	0.11	0.31	0	0
UTILIZE	Quantity of woody residues utilized in a mill. Continuous variable (green tons per month).	208	3,460	8,138	800	61,000
DISPOSE	Quantity of woody residues generated in a mill as waste and disposed of by reusing, selling, giving away or sending to a landfill (green tons per month).	182	2,680	6,038	750	51,900
LOGRESID	Amount of logging residues utilized in a mill in addition to mill residues (green tons per month).	19	2,517	4,032	440	15,000
UPGRADE	Equipment upgrade plans. A binary variable: 1 if a mill planned future upgrades to produce electricity from woody residues, 0 if not.	239	0.08	0.26	0	
Procurement characteristics						
PRICE	Maximum gate price a mill was willing to pay for additional logging residues (US$ per green ton).	34	11.92	9.95	15.00	35
HAUL	Maximum actual hauling distance over which logging residues were delivered (miles).	39	49	45	45	200
EHAUL	Maximum economic hauling distance over which logging residues can be delivered (miles).	68	58	42	50	200
Mill-management opinions toward factors limiting utilization of additional quantities of logging residues						
TCOST	Importance of high transportation cost in utilization of additional logging residues. A binary variable: 1 if important, 0 otherwise.	153	0.78	0.42	1	
STORE	Importance of lack of storage space at a mill in the utilization of additional logging residues. A binary variable: 1 if important, 0 otherwise.	153	0.68	0.47	1	
EQUIP	Importance of lack of equipment to handle logging residues at a mill in the utilization of additional logging residues. A binary variable: 1 if important, 0 otherwise.	156	0.70	0.46	1	
RESID	Importance of limited availability of logging residues in the utilization of additional logging residues. A binary variable: 1 if important, 0 otherwise.	145	0.48	0.5	0	
MILLCAP	Importance of lack of processing capacity at a mill in the utilization of additional logging residues. A binary variable: 1 if important, 0 otherwise.	150	0.75	0.43	1	
OTHER	Other important factors in utilization of additional logging residues. A binary variable: 1 if important, 0 otherwise.	36	0.53	0.51	1	

Note: Max, maximum; *N*, number of observations; SD, standard deviation.
UTILIZE, LOGRESID, and DISPOSAL were continuous variables measured in green tons per month (50 percent moisture content). UPGRADE and WILLING were binary variables with Yes or No answers. TCOST, STORAGE, EQUIP, RESID, and MILLCAP were originally measured on a 5-point Likert scale and reclassified into binary variables with responses coded as important or not important. Important designation included original Linkert scale categories corresponding to "3—moderately important," "4—important," and "5—very important," whereas not important designation included Linkert scale categories corresponding to "1—unimportant" and "2—of little importance."

to 1.63, 2.57, and 2.30 million bdt, respectively. The lowest possible extraction levels with a 35-mile hauling distance were reported in Oklahoma (84 percent, 0.17 million bdt) and Florida (94 percent, 1.16 million bdt). At a 45-mile hauling distance, all states would be able to recover at least 98 percent

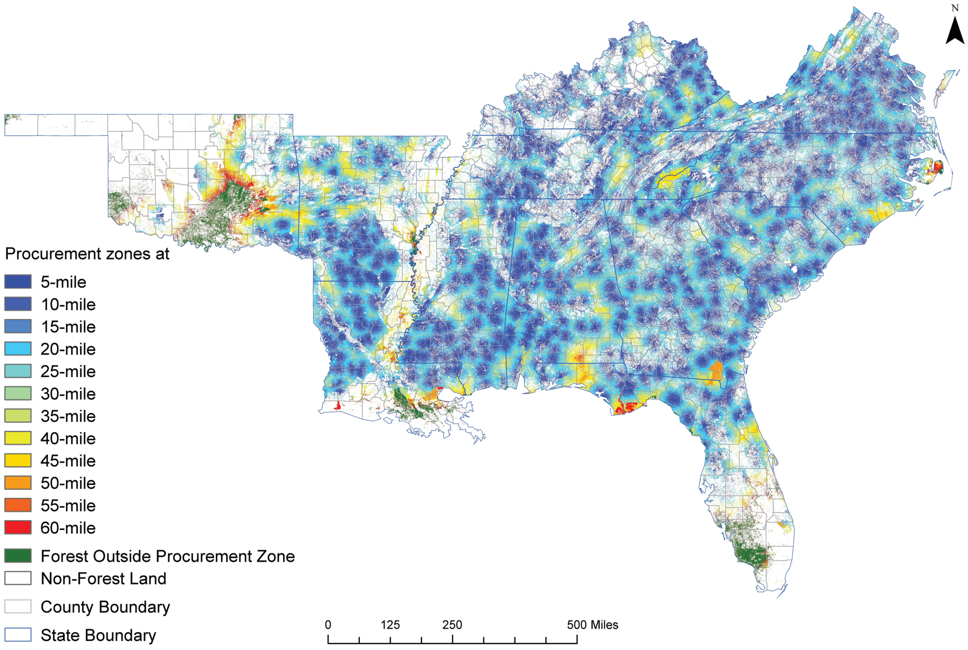

Figure 6. Procurement areas around individual mills in the southern United States generated using 5-, 10-, 15-, 20-, 25-, 30-, 35-, 40-, 45-, 50-, 55-, and 60-mile hauling distances.

of their logging residues except Oklahoma, which would be able to recover 95 percent. At a 60-mile hauling distance, all states would be able to recover 100 percent of their logging residues.

Descriptive and Comparative Statistics

An adjusted response rate of the mail survey of mill management was 20 percent and was comparable to other mail surveys conducted in the study area by Conrad et al. (2011) and Joshi et al. (2014). Three statistical tests revealed an absence of nonresponse bias in the survey data ($P > .10$).

A limited number of mills, approximately 4 percent, reported utilizing logging residues to produce electricity in addition to utilizing mill and other woody residues, whereas 11 percent of the owners and managers were willing to utilize additional quantities of logging residues to produce electricity. On average, 2,517 gt/month (median = 440 gt/month, $n = 19$) of logging residues were utilized in a mill, whereas the average utilization of all types of woody residues (including mill residues, logging residues, and other woody waste) was 3,460 gt/month (median = 800 gt/month, $n = 208$, Table 1). Mill managers reported a different quantity of currently utilized logging residues to produce electricity, depending on whether the mill management was willing or not willing to utilize additional logging residues ($P = .045$). Mill managers willing to use additional logging residues reported an average utilization of 550 gt/month of logging residues (median = 350 gt/month, $n = 4$), and those not willing to use more reported 3,259 gt/month (median = 720 gt/month, $n = 14$) (Table 3). A small number of mill managers and owners (8 percent) anticipated implementing equipment upgrades to facilitate electricity production in the near future. Although almost 35 percent of those willing to utilize additional quantities of logging residues were planning such upgrades, only 5 percent of managers and owners not willing to use additional quantities ($n = 191$) anticipated future upgrades ($P = .000$).

Mill managers were willing to pay on average US$11.92/gt (median = US$15/gt, $n = 34$) for logging residues at the gate. Managers were willing to pay as much as 17.25/gt ($n = 13$) if they were willing to utilize additional logging residues compared to those who were not willing (US$9.05/gt, $n = 20$) to use additional quantities ($P = .017$). The average hauling distance to recover logging residues from a harvest site was 49 miles (median = 45 miles, $n = 39$). Mill managers indicated that, on average, they could economically haul logging residues up to 58 miles (median = 50 miles, $n = 68$). The maximum economically feasible distances for hauling logging residues were different for mills where the management was willing (69 miles) and not willing (46 miles) to utilize additional quantities of logging residues ($P = .036$). The difference was not significant for actual hauling distances ($P > .10$). There was also no difference in responses of management (willing and not willing to use additional logging residues) for

Table 2. Quantities of potentially recoverable logging residues in procurement zones based on 5-, 10-, 15-, 20-, 25-, 30-, 35, 40-, 45-, 50-, 55-, and 60-mile hauling distances and existing transportation networks in the southern United States (percentage of total physically available logging residues in a state is reported in parenthesis).

	Quantity of recoverable logging residues (1,000 bone dry tons per year) from a milling facility by a hauling distance												
State	5 miles	10 miles	15 miles	20 miles	25 miles	30 miles	35 miles	40 miles	45 miles	50 miles	55 miles	60 miles	Total
Alabama	192	662	1,275	1,801	2,137	2,300	2,382	2,411	2,425	2,434	2,439	2,439	2,439
	(8)	(27)	(52)	(74)	(88)	(94)	(98)	(99)	(99)	(100)	(100)	(100)	
Arkansas	189	654	1,158	1,528	1,754	1,896	2,000	2,054	2,070	2,074	2,077	2,078	2,087
	(9)	(31)	(56)	(74)	(84)	(91)	(96)	(99)	(100)	(100)	(100)	(100)	
Florida	84	292	572	846	1,026	1,121	1,165	1,195	1,215	1,225	1,226	1,237	1,245
	(7)	(24)	(46)	(68)	(83)	(91)	(94)	(97)	(98)	(99)	(99)	(100)	
Georgia	221	783	1,499	2,119	2,514	2,693	2,745	2,759	2,760	2,797	2,797	2,797	2,799
	(8)	(28)	(54)	(76)	(90)	(96)	(98)	(99)	(99)	(100)	(100)	(100)	
Kentucky	254	785	1,247	1,481	1,573	1,613	1,625	1,629	1,630	1,630	1,630	1,630	1,629
	(16)	(48)	(77)	(91)	(97)	(99)	(100)	(100)	(100)	(100)	(100)	(100)	
Louisiana	128	473	916	1,347	1,612	1,725	1,794	1,835	1,857	1,877	1,888	1,892	1,919
	(7)	(25)	(48)	(71)	(85)	(91)	(95)	(97)	(98)	(99)	(100)	(100)	
Mississippi	171	627	1,111	1,451	1,627	1,696	1,737	1,755	1,762	1,774	1,779	1,785	1,795
	(10)	(35)	(62)	(81)	(91)	(95)	(97)	(98)	(99)	(99)	(100)	(100)	
North Carolina	295	983	1,766	2,349	2,686	2,839	2,903	2,931	2,954	2,956	2,957	2,959	2,965
	(10)	(33)	(60)	(79)	(91)	(96)	(98)	(99)	(100)	(100)	(100)	(100)	
Oklahoma	8	33	68	106	132	156	173	185	197	203	205	207	210
	(4)	(16)	(33)	(51)	(64)	(75)	(84)	(90)	(95)	(98)	(99)	(100)	
South Carolina	219	738	1,295	1,778	2,115	2,269	2,297	2,299	2,300	2,300	2,300	2,300	2,305
	(9)	(32)	(56)	(77)	(92)	(99)	(100)	(100)	(100)	(100)	(100)	(100)	
Tennessee	174	536	883	1,086	1,192	1,245	1,275	1,292	1,297	1,297	1,297	1,297	1,297
	(13)	(41)	(68)	(84)	(92)	(96)	(98)	(100)	(100)	(100)	(100)	(100)	
Virginia	297	1,067	1,791	2,223	2,456	2,532	2,560	2,567	2,567	2,567	2,567	2,567	2,567
	(12)	(42)	(70)	(87)	(96)	(99)	(100)	(100)	(100)	(100)	(100)	(100)	
Total	2,231	7,633	13,581	18,114	20,822	22,083	22,656	22,911	23,033	23,135	23,162	23,188	23,257
	(10)	(33)	(59)	(78)	(90)	(95)	(98)	(99)	(99)	(100)	(100)	(100)	

Table 3. Comparative statistics of woody residues utilization, procurement, and factors limiting utilization of additional logging residues between mill management willing and not willing to utilize additional logging residues to produce electricity in the southern United States based on a mail survey conducted in 2012.

	Mill management willing to utilize additional logging residues to produce electricity					Mill management not willing to utilize additional logging residues to produce electricity					Test of difference between two groups (paired *t*-test)
	(WILLING mills)					(NOT WILLING mills)					
Variable	*N*	Mean	SD	Median	Max	*N*	Mean	SD	Median	Max	*P*-value
UTILIZE***	18	8,191	15,952	1,285	61,000	166	2,952	6,718	790	51,900	.0094
DISPOSE	20	3,956	8,512	750	33,000	144	2,593	5,886	723	51,900	.3623
LOGRESID**	4	550	614	350	1,400	14	3,259	4,489	720	15,000	.0455
UPGRADE***	23	0.35	0.49	0	1	191	0.05	0.21	0	1	.0000
PRICE**	13	17.25	8.93	19	35	20	9.05	9.26	8	28	.0173
HAUL	16	61	54	47	200	20	37	34	37	100	.1190
EHAUL**	21	69	43	60	200	41	46	33	40	150	.0361
TCOST	22	0.86	0.35	1	1	119	0.76	0.43	1	1	.2497
STORE	22	0.59	0.50	1	1	119	0.71	0.46	1	1	.3269
EQUIP	22	0.68	0.48	1	1	124	0.72	0.45	1	1	.7452
RESID	21	0.57	0.51	1	1	114	0.44	0.50	1	1	.2783
MILLCAP	22	0.73	0.46	1	1	118	0.76	0.43	1	1	.7378
OTHER	4	0.50	0.58	0.5	1	30	0.50	0.51	0	1	.9999

Note: $^{***}P < .01$, $^{**}P < .05$, $^{*}P < .1$ for the paired *t*-test between two groups: mill management willing and not willing to utilize additional logging residues to produce electricity.

factors limiting utilization of additional logging residues measured as a binary choice of importance and unimportance ($P > .10$).

Likelihood that Mills Would Be Utilizing Additional Logging Residues

The regression model did not suffer from heteroscedasticity (Breusch–Pagan test, $P = .89$) or multicollinearity (variance inflation factor <10 for all variables). Also, the test for endogeneity (Hausman test of endogenous error, $P = .132$) and autocorrelation (Durbin–Watson statistics, DW = 0.05, $P = .71$) rejected the null hypotheses indicating an absence of these problems in the model.

The quantity of woody residues utilized in the mill and anticipated upgrades had a positive association with the probability that mill management would be willing to utilize additional quantities of logging residues to produce electricity ($P < .05$). An increase of 1 percent in utilization of woody residues at a mill was associated with a 9 percent increase in the probability that mill management would be willing to utilize additional residues. Similarly, if mills anticipated upgrades, the probability that mill management would be willing to utilize additional residues was 16 percent higher than those not anticipating upgrades. The quantities of disposable mill residues generated at the mill and where mill management considered lack of storage as an important limitation in the utilization of logging residues were negatively associated with the probability (Table 4). An increase of 1 percent in disposable residues in the mills was associated with an 8 percent decrease in the probability that mill management would be willing to utilize additional logging residues. Similarly, if mill management reported a lack of storage space as an important limiting factor limiting the utilization of additional logging residues, the probability that mill management would be willing to utilize additional residues was 13 percent less than those not considering storage space as an important limitation. However, whether mill management considered high transportation costs, lack of equipment to handle logging residues, logging residue availability, and capacity to process residues as an important factor limiting utilization or not, the probability that mill management would be willing to utilize additional residues for electricity production remained unchanged ($P > .10$).

Discussion

Almost all logging residues (98 percent, 22.66 million bdt) could potentially be recovered and transported to

Table 4. Parameter estimates of a binary logit regression model to determine mill management willingness to utilize additional logging residues to produce electricity in the southern United States based on a mail survey conducted in 2012.

Variables (*n* = 84)	Coefficients (SE)	Marginal effects
Constant	-4.75^{**} (2.49)	–2.49
UTILIZE	1.03^{**} (0.49)	0.09
DISPOSE	-1.08^{**} (0.49)	–0.08
UPGRADE	2.30^{***} (0.86)	0.16
TCOST	2.08 (1.42)	0.15
STORE	-1.87^{**} (0.80)	–0.13
EQIUP	1.58 (1.26)	0.11
RESID	–0.32 (0.84)	–0.02
MILLCAP	0.92 (1.03)	0.07
Log-likelihood	–25.97	

Note: n, number of observations; SE, standard error.
$^{***}P < .01$, $^{**}P < .05$, $^{*}P < .1$.

the nearest mills with a 35-mile haul if all mills started to utilize logging residues. Thus, a greater utilization of logging residues is potentially possible because mills were already hauling residues over distances up to 49 miles. An increased usage may be achieved by increasing the number of mills that would utilize logging residues without increasing hauling costs. The annual aggregated demand can potentially add up to 19.99 million bdt if all 1,324 mills started utilizing logging residues with a current average utilization of 1,258 bdt/month. This feedstock demand represents 85 percent of logging residues available in the region. On the other hand, utilizing logging residues in all mills with smaller processing capacities may be associated with higher operational costs to process sufficiently large volumes of logging residues.

Previous studies related to biomass feedstock logistics suggested that a drop in the delivery cost of biomass by 8 percent (US$40.97–37.89/t) would be associated with feedstock supply increase by 20 percent (Poudel et al. 2016). Therefore, reducing the hauling distance could decrease the delivery cost and increase the feedstock supply. In states such as Kentucky, Virginia, Tennessee, South Carolina, and Mississippi, approximately two-thirds of their available logging residues were located within a 15-mile hauling distance. All states except Oklahoma could potentially utilize 94 percent or more of their logging residues if procurement took place over a 35-mile hauling distance. In the study area, a higher density of mills was observed in Kentucky, Virginia, Carolinas, and Tennessee. This may have contributed to a higher potential of utilizing logging residues at shorter hauling distances in these states. Oklahoma and Florida had a smaller number of mills, mostly concentrated in eastern Oklahoma and northern Florida, and so they had a lower potential of utilizing additional logging residues. Georgia had a relatively large number of mills, and they were distributed evenly across the state such that a potential of utilizing additional logging residues was higher despite a smaller number of mills than in Tennessee, Kentucky, and Virginia.

Although an economically feasible utilization of logging residues within the existing forest products supply system was possible (98 percent of logging residues were physically available within a hauling distance of 35 miles), a relatively small number of mills (4 percent) were using logging residues to generate electricity. Also, the quantity of logging residues utilized was limited in comparison with total woody residues (4 percent of total feedstock). A low utilization level of logging residues in the region was most likely because of unprofitable operations and supply constraints such as lack of equipment to handle logging residues and appropriate trucks to haul them (Spinelli et al. 2014, DOE 2016), and the low value of logging residues (Riffell et al. 2011). Another explanation might be that whereas some mills might be able to recover and cost-effectively transport logging residues, they did not have sufficient capacity to process them and/or were lacking the equipment to convert them into electricity. Previous studies have also shown that economic feasibility was an important factor in limiting the utilization of logging residues (Gan and Smith 2006, Gruchy et al. 2012, White et al. 2013). The price of delivered forest-based woody biomass including logging residues was US$41/gt in US Pacific Northwest, much higher than a delivered price for chips (US$34/gt) (Wood Resources International (WRI) 2017). Based on Timber Mart-South averages, a 35-mile hauling distance corresponded to the transportation cost of US$4.90/gt of logging residues (specifically, pine fuel residues), and the total cost of logging residues delivered at the gate was US$22.00/gt in 2012 (Harris et al. 2012). However, survey responses in this study indicated that mill managers and owners were only willing to pay US$11.92/gt for logging residues at the gate, which was approximately 54 percent of the gate price for delivered logging residues prevalent in the southern United States. This might be a potential explanation for a small number of mills engaged in the utilization of logging residues and their low willingness to use this feedstock for electricity production.

Storage space was an important limitation in the additional utilization of logging residues. Mill managers and owners were not willing to allocate their space to store logging residues. A system to dry logging residues at the landing, as is carried out in Finland and other Scandinavian countries (Nurmi 1999), and to haul them with less moisture content to mills for utilization can reduce transportation costs as well as the need for storage space at the mills. Contrary to previous studies, there was no statistical significance on the association of mill-management perceptions of high transportation costs and lack of equipment to handle logging residues with the probability that a mill would be willing to utilize additional quantities of logging residues. Therefore, mill management's willingness to utilize additional logging residues was not affected by these limitations, although they were important. A possible explanation is that mill management considers them unavoidable, and they will always be a limitation in additional utilization and thus not part of their decisionmaking process. This also points to a status quo where mill management does not want to use logging residues because they consider its procurement and usage financially not feasible for electricity generation.

There was a positive correlation of mill management's willingness to utilize additional quantities of logging residues for electricity production with the current level of woody residue utilization and anticipated equipment upgrades to facilitate electricity production. The finding was consistent with previous studies in the study region (Radhakrishnan et al. 2013, Pokharel et al. 2017a). Mills that were already utilizing logging residues in larger quantities were less interested in utilizing additional quantities of this feedstock. These mills might be already utilizing residues at their full processing capacity or obtaining logging residues at a lower cost from forests nearby. To increase utilization of logging residues, these mills would need capacity upgrades to haul logging residues from harvest sites located farther away. Increases in woody residue utilization, equipment upgrades to facilitate electricity production, and reduction in the quantity of disposable mill residues produced at the mill were positively associated with the probability of utilizing additional logging residues. However, capacity improvements, equipment upgrades, and technological advancements require significant capital investments to produce electricity from woody residues (FEMA 2011, IRENA 2012). In such a case, mills would not be willing to invest in these improvements unless their marginal profit is higher than their marginal cost. Costly capacity improvements and equipment upgrades will depend mainly on the demonstrated potential for profitable operations and utilization of logging residues to produce electricity, as also indicated by previous studies (Jones et al. 2010, Pokharel et al. 2017a, b).

Several policy implications can be drawn from this study. First, local-, state-, and federal-level support mechanisms for technical upgrades of mill infrastructure and financial assistance in the form of investment subsidies and/or low-interest loans to purchase equipment required to handle, transport, and process logging residues might be needed to increase utilization. Financial incentives can include bioenergy production credits, tax breaks, and contracted energy buyback guarantees that would help increase the competitiveness of logging residues as a bioenergy feedstock. Strategies and policies designed to demonstrate economically feasible usage of logging residues in mills or similar facilities may help motivate more mills to use logging residues. An increase in the number of mills processing logging residues might also increase competition and demand for logging residues. This, in turn, would help loggers and truckers invest in collection and transportation equipment and improve logistics of logging residues supply chains, which would facilitate a more cost-effective recovery of logging residues. Policies that promote collaboration between mills, landowners, contractors, and government and nongovernment agencies can facilitate the sharing of resources and identifying more effective solutions to address economic feasibility issues related to the utilization of logging residues. Second, the federal and state agencies such as regional research stations and labs, state departments of land or natural resources, the Bureau of Land Management, US Forest Service, and tribal land-management agencies might invest in and establish facilities that utilize logging residues to produce electricity as an example to motivate mills and understand necessary changes in the supply chain such as Northwest Advanced Renewables Alliance's (NARA) approach to building a supply chain using forest harvest residuals to make aviation biofuel and coproducts (NARA 2016, Martinkus et al. 2017, 2018). Such agencies might also collaborate with existing mills to develop working demonstrations of logging residues utilization to produce electricity and other forms of bioenergy as well as to develop strategies to commercialize these projects. Third, further research is needed to determine the impacts of the price paid for and associated transportation cost of logging residues on mill management's willingness to utilize additional logging residues to produce electricity.

Finally, it is worth noting the limitations of this study. Actual hauling does not always indicate the optimal route between the nearest harvest site and a mill. The distance over which forest products are hauled often depends on the contract between the forest owner, logging contractor, and a mill. Also, the road and bridge weight limits and speed limits on local roads can affect the routes between mills and harvest sites. Estimates of transportation cost were not available and not included in this study. Therefore, the analysis approach can be improved by using locations of mills and corresponding harvest sites and available transportation cost. However, at the time of conducting the study, such data were not available to the authors. The cost estimate of transportation between corresponding harvest sites and a mill can be done by working with the mills and agencies as future research. Including other facilities, such as cogeneration and bioenergy facilities that either already utilize or have the potential to utilize logging residues to produce electricity might improve estimates of logging residues utilization and its economic viability. Also, spatial, temporal, and cross-sectional studies of mills with respect to the forest ownership, transportation infrastructure, loggers, truckers, and other mill types would help explain limited merchantability and identify potential and optimal locations of mills and new facilities to improve the usage of additional logging residues.

Conclusions

Logging residues, a type of biomass left unwanted after logging operations, has been advocated as an alternative feedstock for producing electricity in mills. This study estimated the physical availability of logging residues and determined a probability of utilizing additional quantities of logging residues to generate electricity at a mill. Utilization of logging residues to produce electricity was relatively limited, although most of the physically available logging residues can be recovered within a 35-mile hauling distance in the study area. Strategies and policies targeted toward improving the competitiveness of logging residues might help change mill management's perceptions of this feedstock and increase the number of mills utilizing logging residues. This study concluded that capacity improvements, efficiency upgrades, and decreases in the quantity of disposable mill residues were associated with increased probability of additional usage of logging residues. Mill managers and owners considering storage space as a limiting factor in additional utilization were also less likely to utilize additional logging residues. Therefore, demonstrating the competitive advantage of using logging residues over other forest commodities as well as the bioenergy over energy bought from outside will be important aspects in increasing utilization of additional logging residues. Also, policies related to increasing investments in electricity production, incentives for utilizing logging residues, and instruments and strategies to attract and assist mills in utilizing their additional quantities such as subsidies, technical support, bioenergy buyback guarantee, and legal compliance might help increase the utilization of additional logging residues to produce electricity. Further research should include the impact of the price paid for and transportation cost of logging residues on mill management's willingness to utilize additional logging residues.

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