FOREST RESOURCES FOR BIOENERGY

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Dedication

This dissertation is humbly dedicated to my beloved wife ***Julie Ann***,
children Kurt Dominic & Julia Feliz, sisters and
Nanay Lolang

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Abstract

The overall objective of this dissertation is to evaluate forest resources biomass availability for the production of bioenergy. Chapter II provides measures of the impact that the road sustainability criteria have on the supply of feedstock for forest products and bioenergy. A linear cost minimization programming is used in estimating forest biomass supply curves. Chapter III provides estimates on the changes in US timberland acreages overtime and the ability of timberland to meet conventional timber products and woody biomass demand within the conterminous United States. Chapter IV utilizes the Biofuels Facility Location Analysis Modeling Endeavor (BioFLAME), a Geographic Information System (GIS)-based transportation optimization model to simulate feedstock availability and site economically feasible biorefinery locations, and Impact Analysis for Planning (IMPLAN) model to estimate the economic impact on the biofuels activity in the Southeast region.

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Chapter I: Forest Resources for Bioenergy

Introduction

One of the most valuable resources of the nation is forestland. It provides timber and non-timber values as well as use and non-use values including wildlife habitat and refuge, food and income, recreation and watershed protection among others. The U.S. has a total forestland of 751 million acres, 623 million acres of which are located in the conterminous U.S. (Langholtz et al., 2016). Generally, forestland is composed of hardwood, softwood and mixed wood species. Hardwoods are deciduous, broadleaf trees that shed leaves annually, while softwoods typically are coniferous trees with needle-like leaves (Azuma et al., 1997). Softwoods are dominant in the South, Pacific Northwest and Rocky mountain regions (Alig and Butler, 2004).

Woody biomass is an important source of energy and is widely used as source of renewable energy in the world (Lauri et al., 2014) mostly come from logging residues and non-merchantable timber (He et al., 2014). Lately, forest woody biomass has gained increasing potential for bioenergy production as an alternative to fossil fuels (Pomerening, 2016). Forest biomass includes wood wastes in forests, at mills and from landfills, as well as forest thinnings for fuel reduction and stand improvement (Langholtz et al., 2016). Woody biomass is harvested as an integral component to conventional timber harvesting to reduce the cost of collection and transportation (Rummer, 2007; Harrill and Han, 2012; Langholtz et al., 2016) and represents an opportunity for value addition to harvest of conventional timber (Abt et al., 2015).

Globally, there is also a significant interest in the production of bioenergy from renewable resources for carbon sequestration and greenhouse emission reductions. In 2050, it is projected that woody biomass could supply about 18% of the world's primary energy consumption. In response to concern over energy security, reducing GHG, and mitigating global

warming impacts (Frombo et al., 2009), the U.S. government shifted its priorities and policies towards sustainable environmental protection (Caputo et al., 2005). Forest growth in the U.S. removes approximately 9% of carbon dioxide emissions (South Carolina Forestry Commission, 2016). Moreover, the forest serves as a carbon reservoir because carbon is stored within the tree and not immediately emitted into the atmosphere (Smith et al., 2006). The Energy Independence and Security Act of 2007 expanded the Renewable Fuel Standards (RFS) program to increase cellulosic biofuel production to 16 billion gallons and 21 billion gallons of "advanced fuels" sources by year 2022 (US Environmental Protection Agency, 2016). The collection of logging residues and whole-tree biomass can potentially support the required biofuels target set under Renewable Fuel Standards (He et al., 2014) depending on the expansion of cellulosic biofuels (Coyle, 2010). Forests, the largest source of biomass feedstock, could potentially supply about half of the required advanced and cellulosic biofuels by incorporating residues, removals, and thinning (US Department of Energy, 2011). The Southeast region can potentially contribute about 10.5 billion gallons (50%) of advanced biofuels (Bittleman et al., 2010; Lambert et al., 2016) with the Southern forests playing a large part in meeting the goal.

According to the USDA-FAS (2015), the U.S. was the largest exporter of ethanol in 2014, overtaking Brazil. USDA-ERS (2017) reported that 711.08 million gallons or $2 billion of corn ethanol (USDA-FAS, 2015) was exported to different countries that have "blend" mandates. Additionally, the decline in prices of corn have contributed to the increase in corn ethanol production.

Despite the promising economic benefits of collecting biomass for bioenergy and in mitigating climate change, concerns over sustainability of forestry practices and the efficiency of bioenergy conversion technologies must be addressed (Smith et al., 2006). For instance, the land

use conversion, harvesting of logging residues and small diameter trees for biofuels affects not only biological diversity (Innes, 2013) but also may degrade the soil and reduce water quality.

Sustainable forest management contributes to improved water quality, better soil protection and carbon sequestration. Better forest protection and forest health management through compliance with best forest management practices could lead to excellent forest growth, tree quality, sizes, and volumes (Smith et al., 2003). Hence, economic benefits must be balanced with environmental and ecological protection towards sustainable extraction of forest resources.

The objectives of this Study are to

- Provide measures of the impact that the road sustainability criteria have on the supply of feedstock for forest products and bioenergy;
- Provide estimates of the changes of South timberland acreages over time and its ability to meet conventional timber products and woody biomass demand within the conterminous U.S.; and
- Simulate feedstock availability and site economically feasible biorefinery locations and to estimate the economic impact of the biofuels activity in the Southeastern region

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Chapter II: The Impact of Sustainability Criterion on Forest Residue Availability in the U.S.

Abstract

Concerns over climate change and fossil fuel availability substantially shifted policy direction towards the use of renewable energy to reduce fossil fuel and associated greenhouse gas emissions. Cellulosic woody biomass as a potential renewable energy feedstock is a viable alternative to fossil fuels. The Energy Independence and Security Act of 2007 mandated an increase use of cellulosic biofuels under the expanded Renewable Fuel Standards. Forest woody biomass resource has the potential to meet some of the required feedstock demand. Recently, there has been a considerable efficiency improvement in cellulosic biofuel technologies to convert woody biomass into biofuels. This study focuses on the utilization of forest logging residues and whole-tree woody biomass as potential feedstock to cellulosic biofuel production. Specifically, it provides measures of the impact on the sustainability criterion on forest residues availability for bioenergy. Sustainability issues may include a) building of temporary roads that may impact streams and water quality, soil erosion, wildlife habitat and refuge, b) restriction on timber harvest relative to timber growth rate. Thus cannot harvest more than the growth rather previously timber harvested acres are allowed to grow and regenerate until it become class 2, and c) cable yarding system harvesting are assumed applicable only to areas greater than 40% slope to prevent soil erosion and damage to forest floor. Consequently, no residues are collected in these areas. A Forest Sustainable Economic and Analysis Model (ForSEAM), a linear cost minimization model is used to simulate woody biomass supply curves over time to meet conventional timber and bioenergy demand. Results showed that at marginal price of $40-$80 per dry ton, the total available potential woody biomass feedstock in the conterminous U.S. ranged from 21 million dry tons to 133 million dry tons under ½-mile road distance and up to 254 million dry tons under the 1-mile road distance for the period 2020 to 2040. However,

extending the modeling period from 2045 to 2055, the 1-mile scenario's potential biomass supply is about 120 million dry tons at $80 per dry ton while the ½-mile have produced much lesser biomass supply. The baseline scenario assumes that moderate conventional timber products demand, less logging residues availability and more whole-tree biomass will be available for bioenergy. This scenario implies that with higher demand for conventional timber products, more logging residues are available for harvest and a reduced level of whole-tree biomass. At $60 per dry ton, the majority of the harvested whole-tree hardwood and mixed woody biomass are located in the south region while softwoods are harvested in the south and west regions. Private timberlands supplied most of the woody biomass.

Estimated quantities of available biomass decrease with time because of the limited timberland acres available and low yield. For instance, the acres harvested in previous years are no longer available for harvest in the succeeding years until the timberland regenerates back to either class 1 or one harvest rotation. Additionally, the model assumes that timber harvest cannot exceed timber growth and volume in any given year.

Introduction

The U.S. generates approximately 11 gigawatts of renewable energy and about 20% of that comes from forest biomass (Harrill and Han, 2012). At present, more than 30 small-scale U.S. firms are engaged in technology innovation on forest biomass to produce cellulosic biofuels (Coyle, 2010). Accordingly, there is a need to improve the feedstock supply to meet the demand of today's bioenergy development (USDA-ERS, 2016). In 2014, the U.S. was the largest ethanol exporter after it overtook Brazil in ethanol production (USDA-FAS, 2016). ERS-USDA (2017) reported that about 711 million gallons of corn ethanol valued at $2 billion was exported to different countries especially those with "blend" mandates, and that the decline in prices of corn commodity had contributed to the increase in corn ethanol production (USDA-FAS, 2015).

In an effort to reduce greenhouse gas emissions, renewable energy sources are growing worldwide (Rewald et al., 2014). Bioenergy is capable of replacing fossil-based energy that is currently used for heating, electricity and transportation (Guo et al., 2015). Recent trends show that the U.S. Government has placed significant resources in the production of bioenergy for carbon sequestration and reduced greenhouse emissions toward sustainable environmental protection (Caputo et al., 2005) and mitigation of global warming impacts (Frombo et al., 2009). Under the U.S. Energy Independence and Security Act (EISA) of 2007, the Renewable Fuel Standards (RFS) program established a nested biofuel production requirement. It was expanded to increase biofuel product to 36 billion gallons with no more than 15 billion gallons of ethanol derived from corn. The additional 21 billion gallons of "advanced fuels" were to be made up of at least 16 billion gallons of cellulosic biofuels by year 2022 (US-EPA, 2016). With RFS2, obliged parties must comply by blending renewable fuels into transportation fuel or obtain credits "Renewable Identification Numbers" (RIN) to meet their specified Renewable Volume

Obligation (US-EPA, 2016). These RINs are similar with emission trading permits that a firm can either sell excess RINs on biofuel production or purchase RINs to cover deficits (Zhang et al., 2016; Westcott and McPhail, 2013). Commercial cellulosic biofuel production began in 2013 (US-EPA, 2016). At present, the production of commercial biofuel from logging residues is not widely available (Pomerening, 2016). A second criterion for a fuel to be an advanced biofuel is that biofuels produced from cellulose, hemicellulose, or lignin must reduce by 60% lifecycle GHG emission relative to life-cycle emissions from fossil fuels as required under EISA 2007 (US-EPA, 2016). The volume of the biomass feedstock could potentially increase (Langholtz et al., 2016) depending on costs and effectiveness of the new commercial technology to process woody residues to biofuels (Gehlhar et al., 2010).

Forests are an important economic resource for the solid wood and paper industries and other forest-based investments (He et al., 2016). Eight percent of the world's forestland is in the U.S. That forestland contains, 10% of the earth's total forest timber inventory, and provides feedstock for an estimated 28% of the world's industrial products (Oswalt et al., 2013). Thus, forest residues can be a substantial feedstock for energy production (Greene et al., 2007) when harvested simultaneously during conventional timber harvesting (Langholtz et al., 2016) or after conducting silvicultural operations (NREL, 2016) and can be readily harvested for bioenergy (Galik et al., 2009). NREL (2016) reported that 65% of logging residues and 50% of other removals can be collected as biomass and the remainder left in the field to maintain the ecosystem. In 2009, Galik et al (2009) projected that forest logging biomass could provide up to 6.9 million dry tons depending on marginal prices. In 2006, the U.S. net annual timber growth increased by 2.8% equivalent to 26.7 billion ft^3 and 13% of the growth originated on private timberlands that are mostly located in the South, with average yield at nearly 55 ft^3 per acre

(Conner and Michael, 2009). While roundwood pulp and residues are likely to be the potential bioenergy feedstock, increasing demand for bioenergy will likely impact prices and availability of wood resources for conventional timber products (Galik et al., 2009).

With increasing interest in biofuels production, forest biomass can potentially contribute to the Renewable Fuel Standards program (He et al., 2014) and have important economic impacts (He et al., 2016) in the overall economy, trade, and consumption by reducing the volume of petroleum (Gehlhar et al., 2010). Langholtz et al (2016) reported that the U.S. has an estimated potential feedstock supply of about one billion dry tons annually until 2040 from various renewable nonfood energy sources such as agriculture, forest biomass, algae and wood waste. Moreover, they added that forest biomass from logging residues, small diameter trees and forest thinning is projected to contribute from 20 million dry tons to 185 million dry tons to feedstock supply at marginal prices ranging from $40/dry ton to $80/dry ton, respectively. Currently, the conterminous U.S. has 623 million acres of forestland (Langholtz et al., 2016) of which 475 million acres are classified as timberland[1]. The majority of the harvested biomass comes from privately owned forestlands (Perry et al., 2008) and mostly (87%) in the South. The South Central region is expected to increase its timberland area by 0.2%, due to afforestation of some agricultural lands. Meanwhile Southeast and Pacific Northwest nonindustrial private timberlands, because of development, are expected to decline by 0.4% and 0.1%, respectively (Haynes et al., 2007). Other forestlands classified as reserved or not capable of producing 20 ft^3 per acre per year of timber are important to watershed protection, wildlife habitat and refuge, domestic livestock grazing, recreation, and biodiversity. These lands are not included in the analysis.

[1] A forestland capable of producing industrial wood annually that meets minimum productivity requirement (Brad et al., 2009).

The sustainability of forest resources productivity and harvesting is important to forest management. One of the issues in timber harvesting is road construction and compliance to forest best management practices. While forest roads are important to accessing forests for timber harvesting and recreation, they can cause more erosion than any other aspect of logging. That happens when sediment washes away from timber harvesting operations. Erosion usually occurs along poorly built forest roads and can create a compacted surface within woodlands (Ochterski, 2004), blocking water movement through soil (Moesswilde, 2004). As more water accumulates, a channel is formed and erosion begins; in addition, harvesting can cause streams to erode by blocking the stream's flow with debris. Aside from the environmental concerns, road construction requires additional costs and compliance. With current logging road standards, forestland owners must consider costs and volume of timber hauled, road length and schedules, and type of trucks and equipment (Shaffer, 2005; Geyik, 1986). In some situations, road construction may even require compliance to special conditions associated with Clean Water Act (USDA, 2012).

This study aims to provide measures of the impact that the road sustainability criteria has on the supply of feedstock for forest products and bioenergy. In the *Billion Ton Study* (Langholtz et al., 2016), the supply of timber was restricted to ½-mile (distance between timber and an existing road). This analysis increases that distance to one mile thus adding more timberland to the model. Results of this study could be utilized by policy makers and foresters interested in forest biomass production and supply for bioenergy.

Methodologies for Supply Analysis

Several studies have been conducted and different models have been developed to estimate supply curves and demand of conventional timber products and forest biomass.

Prestemon and Abt (2002) examined the traditional wood products given timber and land acreage, supply and demand relative to prices and income at different scenarios using a partial equilibrium forest's sector model. During the modeling period, they assumed that timber, land use, supply and demand were constant. Public and "non-productive" lands are also excluded. Findings showed that pine plantation acreage potentially increased by 21 to 26 million and industrial wood output by about 50% between 1995 and 2040. Using the Global Biosphere Management Model, a global partial equilibrium model of forest and agricultural sectors, Lauri et al (2014) estimated a global woody biomass supply curve of harvesting logging residues along with traditional timber harvest. Results revealed that at low energy wood prices of \$36/m^3, feedstock supply could come from forest industry by-products but when prices exceed \$36/m^3, logging residues and non-merchantable timber become the most important woody biomass for bioenergy.

Southgate and Shakya (1996) conducted a study in Ohio using a linear programming model to project potential supply of wood bioenergy resources for power plants. Results suggest that utilization of wood and forest residues are likely to increase in commercial electricity. He et al (2014) also developed a linear cost minimization model across the conterminous U.S. to identify regional supply of woody biomass to meet conventional wood timber production targets. They found that the estimated volume of logging residues and non-merchantable woody biomass could potentially meet some bioenergy supply goals until 2030. In fact, as demand increases for conventional timber products, the volume of biomass residues increased from 56 million dry tons to 70 million dry tons when priced at \$60 per dry ton. In addition, He et al (2016) used the Southern Woody Biomass Supply model (SWBioS), a forest biomass linear optimization model to forecast woody biomass supply, and evaluated the comparative advantage of the southern

region in biomass supply given demand, resource constraints and harvesting costs. Results showed that the potential economic benefits increase if logging residues are harvested with the merchantable timber. About 38 million dry tons annually from 2015 to 2030 could be available at a price of less than or equal to $60 per dry ton.

The *Billion Ton Study* (BTS) was conducted to estimate available woody biomass supply in the U.S. and to assess the availability of biomass for bioenergy at the county level (Perlack et al., 2005). They wrote that biomass domestic consumption constitutes about 3% of the total renewable energy source and currently, the sole renewable source in liquid transportation fuel. An update of BTS was also conducted in 2011 to estimate woody biomass supply under different scenarios at a higher geographic resolution. In 2016, the updated BTS reported that at 5% harvesting intensity of forest biomass on existing forest stand volume in any given year is sufficient to meet the future demand (Langholtz et al., 2016).

The Forest Sustainable and Economic Analysis Model (ForSEAM), a linear cost minimization model designed to analyze sustainable biomass supply availability for bioenergy while meeting the demands for traditional timber products was used in the 2016 Billion Ton report (Langholtz et al., 2016). Several sustainability criteria are embedded in the ForSEAM model. These criteria attempt to ensure a balance between timber production and the rigorous environmental requirements on forestland management. ForSEAM has several constraints and assumptions to mimic forest resource sustainability:

- The forest growth rate. *The model explicitly calculates the volume of wood harvested and compares that to the forest growth rate as estimated from FIA data. The volume harvested must be less than the annual growth rate.*

- All protected and reserved forestlands are excluded. *These lands are not included in the analysis because regulatory laws explicitly do not allow such disturbance for commercial purposes. Most often harvesting in the reserved lands are done only for forest health, productivity and to minimize risk of wildfire*.
- A limit on forest harvesting activities. *Harvest cannot exceed 5% of the available timberland acreages at the state level to ensure forest long-term productivity and maintain forest cover.*
- Harvest on steep sites. *The model specifies that, in the Pacific Northwest and Inland West regions where cut-to-length harvesting is applicable, timberland areas greater than 40% slope can be harvested using a cable yarding system, but no woody biomass and logging residues are available.*
- Residue cover is required. *Seventy percent of the logging residues on timberland with less than 40% slope are available assuming that 30% of the residues are retained on the forest after harvest to protect the site and maintain soil carbon and nutrients. Perlack et al (2005) stated that on average about 60% of logging residues can be potentially recovered with the conventional forest harvesting systems. Langholtz et al (2016) increased that amount to 65-70% with newer technology*.
- No Road Construction is allowed. *In adherence to the forest best management practices, ForSEAM also assumes no forest road construction and only forest tracts located less than ½-mile from an existing road are harvested. This is placed in the model to minimize impacts on forest water quality and soil erosion*.

While harvesting whole-tree biomass and logging residues beyond the ½-mile distance may potentially increase the supply of biomass, it will also incur additional costs. The USDA-Forest Service (2003) emphasized that temporary roads are not part of the forest transportation system and not necessary for long-term resource management, the ½-mile distance serves as the upper limit of temporary road construction as part of environmental protection.

Other important assumptions in the model include the following:

- No conversion of natural stands to plantations and/or land cover changes in the model (fast-growing plantations specifically for biomass will not be established after the harvest of a natural stand);
- all harvested stands were assumed to regenerate back to their original cover such that natural stands will either regenerate to hardwood, softwoods, or mixed;
- Plantations will regenerate as plantations;
- Small-diameter stands are allowed to grow to either class 2 or class 1 stands; and
- No forestland losses over the modeling time period

Data and Methods

Data Sources

The ForSEAM utilizes data on timberland acreage, forest stand type, growth and volume, ownership and locations, yield of logging residues from merchantable and non-merchantable, harvesting cost, stumpage cost and chipping cost for harvesting different types woody biomass and conventional timber products (Langholtz et al., 2016). There are 305 regions in the model constructed by aggregating counties to USDA's Crop Reporting Districts (CRD) (Figure 1).

Available timberland acreages of hardwood, softwood and mixed stands including the growth and volume, and biomass yield in geographic locations were estimated from the Forest

Inventory Analysis (FIA) database. The FIA program assesses forestland condition, volume, growth and removals of timber integral to Forest Health Monitoring in every state (O'Connell et al., 2014). Data were aggregated to the CRD level for analysis. The stand net annual average volume in every inventory period was calculated as the incremental change in the net volume of trees minus tree mortality volume and net volume of culled trees during the year (He et al., 2016). Sawlog and pulpwood volume (in cubic feet) and yield of logging residues and non-merchantable timber (in dry tons) available for harvest were calculated on a per acre basis (He et al., 2016) based on the stand classes classified using the diameter at breast height (DBH). Class 1 if stand is >11 inches DBH for hardwood, and >9 DBH for softwood, Class 2 of stand is between 5 inches DBH and ≤11 inches DBH for hardwood, and between 5 inches DBH ≤9 inches for softwood stand, and Class 3 if DBH is <5 inches (saplings) for all stand types.

Methods

ForSEAM was used to estimate woody biomass potential in the 2016 Billion-Ton report. Its predecessors were used in the Billion Ton Update (Perlack et al., 2011) and an economic impact analysis conducted in 2013. The model structure and parameters to simulate conventional timber products demand and target goals for biomass supply curves are similar to those used for the 2016 BTS. Detailed methods are found in Langholtz et al (2016). An alternative scenario is developed to examine the ½-mile distance to road limitation used in the 2016 *Billion Ton Study*. The area of land allowed to be harvested was increased to one mile and compared to the moderate housing and low energy baseline results used in the billion ton Baseline Scenario. In addition, both scenarios' time periods were changed for the period 2015-2040 used in the 2016 BTS to 2015-2055. Therefore, the scenario used in this study included Baseline Moderate

Housing and Low wood energy demand[2] with two alternative harvest potentials defined by available timber at a) ½-mile road harvest distance and b) 1-mile road harvest distance.

Increasing the harvest distance to road from ½-mile to 1-mile increases the availability of timberland to produce both traditional products as well as biomass. Approximately 94% of the timberlands in the U.S. are located within the one (1) mile road distance.

ForSEAM requires data on harvesting and stumpage costs for removing timber products and price and cost to produce end products. The model solves by minimizing the total costs of harvesting, stumpage and chipping subject to

- production target goals of conventional timber wood products and woody biomass as energy feedstock,
- land availability for both conventional timber and whole-tree biomass,
- timber growth,
- logging residues, and
- inter-period class determination

Feedstocks considered in the analysis were forest logging residues and whole tree biomass. The traditional product demand levels used throughout the analysis are similar to that of the 2016 BTS. The biomass target levels were varied ranging from 1 million dry tons to 300 million dry tons at 1-million dry ton increments.

As formulated, ForSEAM has about 6 groups of decision variables (about 30,000) and 17 groups of constraints forming 189,000 single equations (He-Lambert, 2016). The model

[2] Baseline: Growth in wood biomass demand for energy-low; Growth in housing start-Moderate; new plantation management intensity in the south-Moderate; Growth in demand for paper and paperboard-moderate; Growth in demand for biomass do energy, and wood and paper products (foreign)-Moderate.

minimizes the costs of traditional harvest (*X*, *XCTL*), whole tree for biomass harvest (*Z*) and logging residue collection (*U)* (Equation 1). The mathematical model objective function is:

$$minimize\ COST = \sum_{i=1}^{305}\sum_{j=1}^{5}\sum_{k=1}^{2}\sum_{m=1}^{2}\sum_{c=1}^{2}\Big[\sum_{o=1}^{2}[X_{i,j,k,o,m,c,p,t}\alpha_{i,j,k,c,t}(CL_{i,j,o,m,c} + SC_{i,j,k}) + XCTL_{i,j,k,o=1,m,c,p,t}\alpha_{i,j,k,c,t}(CTL_{i,j,m,c} + SC_{i,j,k})\ \Big] + \sum_{i=1}^{305}\sum_{j=1}^{5}\sum_{k=2}^{3}\sum_{m=1}^{2}\sum_{c=1}^{2}\sum_{o=1}^{2}[Z_{i,j,k,o,m,c,t}\beta_{i,j,k,c,t}(CW_{i,j,o,m,c} + SC_{i,j,k}) + \sum_{i=1}^{305}\sum_{j=1}^{5}\sum_{k=1}^{2}\sum_{m=1}^{2}\sum_{c=1}^{2}\sum_{o=1}^{2}[U_{i,j,k,o,m,c,t}\theta_{i,j,k,c,t}(CR_{i,j,m,c} + SCR_{i,j,k}) \quad (1)$$

c = Harvesting options, c=1 thinning (partial cut) and c=2 clearcut

i = CRD 1,…,305

j = stand type *j*=1 upland hardwood *j*=2 lowland hardwood *j*=3 natural softwood, *j*=4 planted softwood, and *j*=5 mixed wood

k = stand diameter class, *k=1* has a diameter >11 inches for hardwood and >9 inches for softwood, k = 2 has diameter range ≥5 inches but <11 inches for hardwood and ≥5 inches but <9 inches for softwood, and k = 3 has diameter <5 inches for all stand types

m = Slope of the land, *m* = 1 slope is ≤40% and *m*=2 has a slope of ≥40%

o = Ownership of the forestland, *o*=1 private and *o*=2 federal

p = Conventional timber product type, p=1 sawtimber and p=2 pulpwood

t = time period

Where:

$X_{i,j,k,m,c,p,t}$ acreage decision variables of timberland full tree harvested to meet conventional demand in Crop Reporting District *i*, by stand type *j*; by stand diameter class *k*; by conventional timber product type *p*; by Ownership *o*;

$\alpha_{i,j,k,c,t}$ 2015 log yield in POLYSIS region *i*, stand type *j*, stand diameter class *k*, cutting options *c*, conventional timber product type *p* at time *t*;

$CL_{i,j,m,c}$ log harvesting costs for partial cut and clear trees (*$ per dry ton*) in Crop Reporting District *i* for tree species *j*, land slope *m*, and cutting option *c* (*$ per acre*);

$SC_{i,j,k}$ log stumpage costs (*$ per dry ton*) in Crop Reporting District *i* for tree species *j*, and stand diameter class *k* (*$ per acre*);

$XCTL_{i,j,k,m,c}$ acres of timberland that were harvested using cut-to-length logging option in Crop Reporting District i for tree species j, stand diameter class k, land slope m, and cutting option c and conventional wood product p at time period t and only private timberland harvested using cut-to-length method;

$CTL_{i,j,m,c}$ logging harvest costs for cut-to-length (CTL) (*$ per dry ton*) in Crop Reporting District i for tree species j, land slope m, and cutting option c (*$ per acre*);

$Z_{i,j,k,m,c,t}$ acres of timberland classified as class 2 and class 3 whole trees harvested to meet woody biomass demand for all $i, j, m, t, c, k = 2,3$;

$\beta_{i,j,k,c,t}$ whole tree yield in Crop Reporting District i for tree species j, stand diameter class k, cutting option c, and time t;

$CW_{i,j,m,c}$ whole tree harvesting costs for partial cut and cleared trees in Crop Reporting District i for tree species j, land slope m, and cutting option c (*$ per acre*);

$U_{i,j,k,m,c,t}$ acres of logging residue harvested to meet woody biomass demand for all i, j, k, m, c, t;

$\theta_{i,j,k,c,t}$ logging residue yield in Crop Reporting District i for tree species j, stand diameter class k, cutting option c and time t;

$CR_{i,j,m,c}$ logging residue harvesting costs for partial cut trees and clear-cut trees in Crop Reporting District i for tree species j, land slope m, and cutting option c;

$SCR_{i,j,k}$ Stumpage costs of logging residues in Crop Reporting District i for tree species j, and stand diameter class k.

This objective function is subject to several constraints including projected demands for feedstocks to meet traditional forest product demands, land availability, regeneration, and sustainability constraints. In this analysis, a single scenario with two different Demand Levels were evaluated and compared. The baseline scenario solution was selected from the set of six analyzed in the Billion-Ton report (Langholtz et al., 2016). In the Demand Level Solution, one of the sustainability criteria was no additional road building that limits the amount of land that can be harvested by requiring that the timberland must be within ½-mile of a road system. Additional land could be utilized if this limit is extended to 1-mile distance. The impacts of this additional

land being available for wood product production is evaluated under land availability scenarios of 1-mile road harvest distance and ½-mile road distance, respectively.

An important facet of the ForSEAM model is the regeneration of forests on previously harvested lands. Forest area regrowth once harvested is tracked in the model and that land does not become available for harvest again until it reaches a 5” diameter or becomes classified as Stand Class 2. Therefore, land will be in trees but that land is not available for harvest.

The 2016 BTS covered about 385 million timberland acres in the conterminous U.S. that was located within ½-mile of an existing road. It includes both the private and public timberlands with slope LE40 in most regions and some GT40 particularly in Inland West and North Pacific regions. However, in this study, the model was modified and acreages of timberland for harvest were extended up to 1-mile of a harvest road distance (Figure 2).

Results

The National Demand Scenario under 2016 Billion Ton Study

Since its inception, the BTS update continues to address issues on whether the biomass for energy supply is adequate to propel production of biofuels relative to the mandated national energy goals, and at what market price. As evidenced, at $40 per dry ton the potential biomass supply ranged 20 million dry tons to 185 million dry tons at $80 per dry ton (Langholtz et al., 2016). Meantime, in 2017 through 2040, the combined agricultural and forest biomass contribute between 137 to 142 million dry tons at $60 per dry ton, and short rotation energy crops has the potential to supply 411 million dry tons. However, forest logging residues and whole-tree biomass alone harvested from private and public lands, have potential biomass supply of 21 million dry tons to 116 million dry tons depending on the marginal price. At $40 per dry ton,

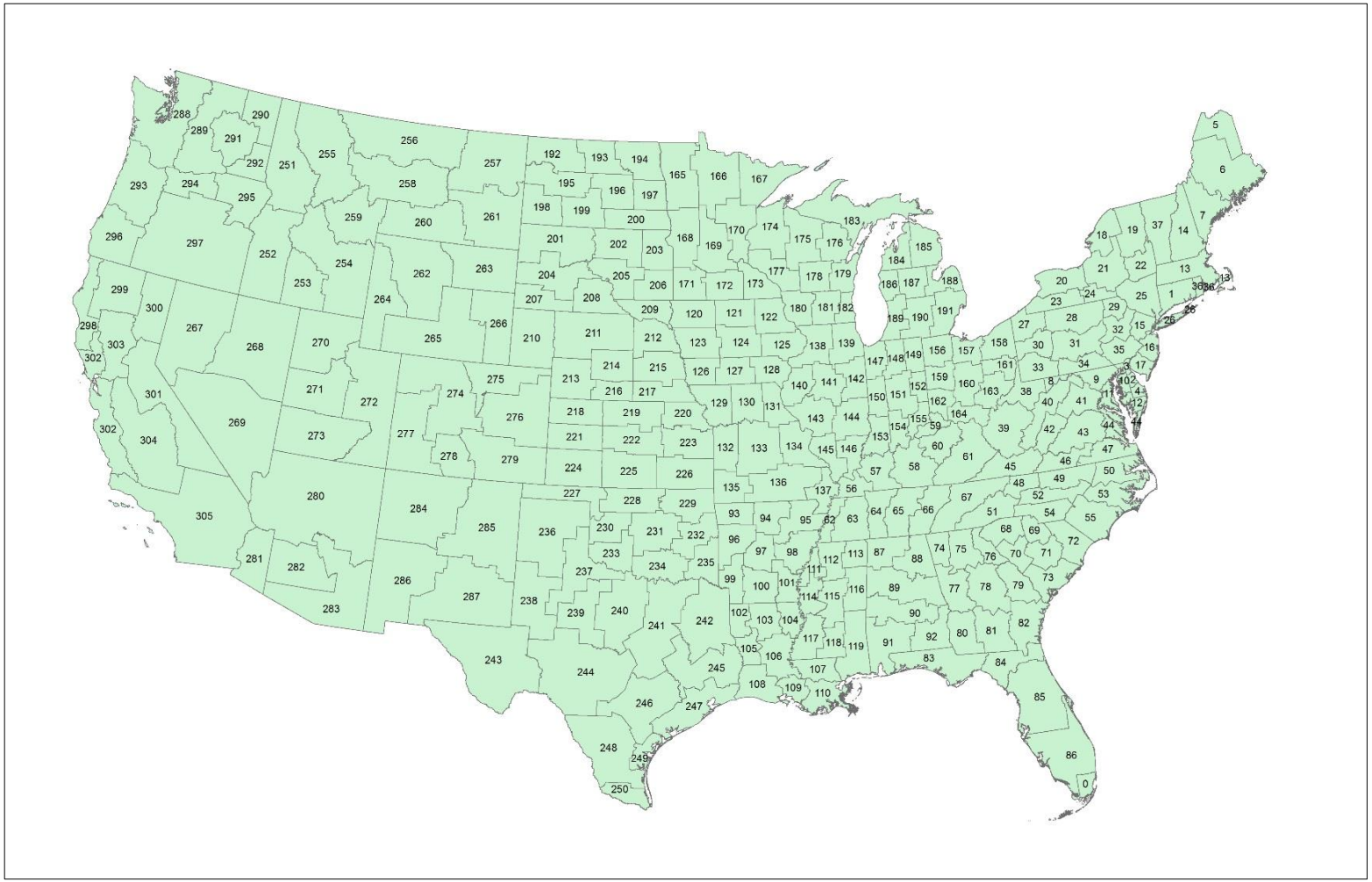

Figure 1. USDA Crop Reporting Districts

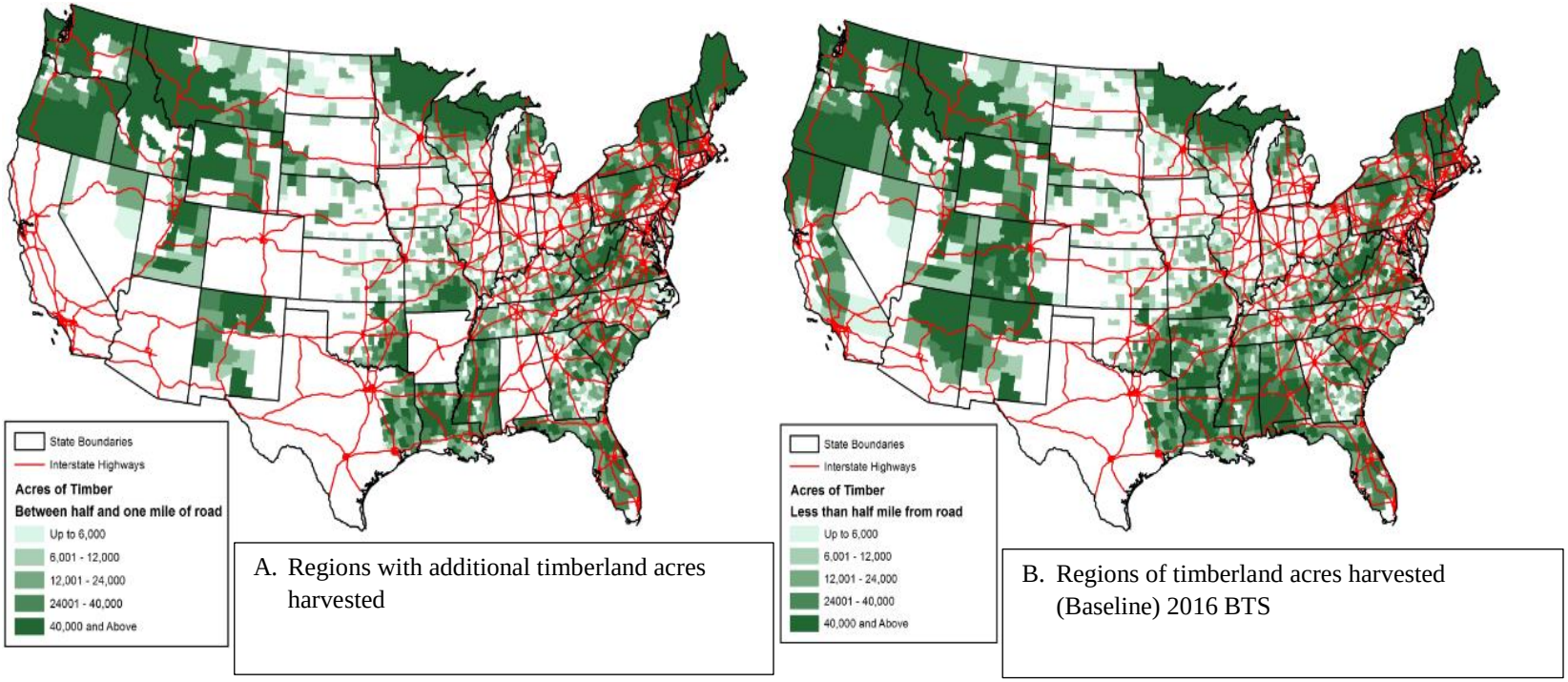

Figure 2. Deviations in timberland acres harvested from the 2016 BTS Baseline

about 21 million dry tons is available mostly (85%) come from logging residues due to lower cost of harvesting compared to whole-tree small diameter trees. At $60 per dry ton, biomass potential supply runs from 82 million dry tons to 88 million dry tons. However, at $80 per dry ton, the estimated maximum potential supply of biomass is 116 million dry tons. Similarly, acres harvested increases with price rise. For instance, in 2020, acres harvested are 4.4 million, 8 million and 8.9 million at $40, $60 and $80 per dry ton, respectively. At $40 per dry ton, most of the biomass supply are from logging residues. As a result, acreage available for harvest declines about 17% over time from 354.51 million acres in 2020 to 302.4 million acres in 2040 (Figure 8). This explains why supply of available biomass declines over time due to the reduction of available acres for harvest. On the other hand, acres regenerated increases from 30.5 million acres in 2020 to 82.6 million acres until 2040 under the ½-mile road distance scenario. As can be seen on the figure, after 2040, most of the timberlands are have lesser biomass availability for harvest due to restrictions in the model (Figure 8).

The South is the major timber-producing region in the U.S. Most of the harvested timbers are softwoods coming from intensively managed plantations. The use of genetically improved stocks have increased. Thus, these timberlands are huge potential sources of woody cellulosic feedstock for biofuel production. The South is capable of producing 10.5 billion gallons of ethanol (Lambert et al., 2016). The region is projected to continue providing most of woody biomass for bioenergy. Forest woody biomass can significantly provide some 40% of the biofuel requirements under the renewable fuel standards. Increase in the demand for conventional timber will lead to an increase in the available supply of logging residues as well as increase forest landowner income if the residues are collected.

Increasing land availability to 1-mile harvest distance

Woody biomass supply curve

Forest woody biomass supply curves for the baseline scenario solutions at 1-mile land availability and ½-mile land availability are provided in Figure 3. As one would expect, woody biomass supply tends to be a price-elastic commodity. As the biomass price increases, the quantity of woody biomass also increases as indicated in the movement along the supply curve towards the right. Logging residues are harvested first as woody biomass because of lower harvesting costs. At a given price range of $17 to $40 per dry ton, available feedstocks are mostly logging residues located in the South (Figures 4, 5, & 6). Increased demand for lumber, pulpwood and other industrial wood-based products would lead to a higher supply of biomass from logging residues.

Whole-tree biomass supply becomes important when the price exceeds $40 per dry ton (Table 1). Unlike the whole-tree woody biomass where the harvested acres increase relative with prices, supply and acreage harvested of logging residues increases over time because the demand for feedstocks used in forest products increases in a given demand scenario. In 2020, the potential woody biomass supply ranged from 21 million up to 250 million dry tons at $40-$80 per dry ton, respectively under the two scenarios. This is approximately a twelve-fold increase in biomass supply as price increases from $40 to $80 per dry ton. In 2020 through 2030, at a price below $80 per dry ton, more than 200 million dry tons of woody biomass are available. However, the biomass supply declines with time because of the change in land availability. Acres that are previously harvested are no longer available for harvest in the succeeding years until it regenerates back to either a class 2 or class 1 stand. For instance, the 1-mile scenario provided a maximum available potential supply of about 120 million dry tons at $80 per dry ton

in 2045. As can be seen in Figure 3, given the same amount of biomass produced in 2045, the ½-mile scenario no longer provides woody biomass supply unlike the 1-mile scenario. However, harvesting additional acres of biomass increases cost to $175 per dry ton and drives the supply curve to bend to the left. This shows that the marginal cost of producing an additional ton of biomass could be expensive and no longer profitable. In 2040 through 2055, the woody biomass supply declines by 29% from 155 million dry tons to 120 million dry tons. The leftward bend of the supply curve could be attributed to higher marginal costs due to the value of the timberland remaining after the lower cost-higher productive lands have been harvested. Thus, any additional ton of biomass produced would no longer be efficient because it can erode profitability and weaken competitiveness with other bioenergy feedstock.

Acres harvested and supply of biomass

Acres harvested and supply of woody biomass in both logging residue and whole-tree biomass were analyzed at $60 per dry ton marginal price from 2020-2055 (Tables 1, 2, 3, 4 & 5). In 2020, about 10 million timberland acres for logging residue and whole-tree biomass or 2% are available for harvest with a potential biomass supply of about 135 million dry tons (Table 6). The South provides the majority of woody biomass feedstock for bioenergy. At $60 per ton, the total harvested acres in the south region is 5.7 million acres when land limits 1-mile distance and 5.1 million under the ½-mile distance scenario mostly from clearcut operations of class 1 and class 2 stands in private timberlands. Thinning operations are conducted on 2.9 million acres of the total 5.7 million harvested acres.

Clearcut and thinning operations are two recommended silvicultural practices in forest management to improve forest health and increase income. From 2020 to 2055, the total acres harvested decreased by about 64% from 10.2 million acres to 3.7 million acres. Specifically,

private and public timberland harvested acres decreased by about 38% and 82% for logging residue and whole-tree woody biomass, respectively. This is because the model assumes that previously harvested acres re-establish and regenerate back to its original cover. Much of the land that was harvested prior to 2055 has not had sufficient time to regenerate. Class 1 stands are not harvested for bioenergy and no thinning in class 3 stands (Figure 7).

Generally, most of the whole tree biomass supply originates on class 2 stands located in the South. In 2020, the region has the potential to supply about 81.3 million dry tons of woody biomass under the baseline scenario at $60 per dry ton. Of which, 51.3 million dry tons (63%) of biomass are generated from clearcut operation and 29.9 million dry tons (37%) through thinning. Public lands contribute 11% (8.7 million dry tons) of the total woody biomass mostly are harvested in the west region.

Woody biomass supply varies greatly with marginal prices (Figures 4, 5 and 6). At prices below $40 per dry ton, most of the supply are from logging residue (19 million dry tons) because of low harvesting cost. Nevertheless, when price increases to $40 per dry ton, about 2.1 million dry tons are supplied from whole-tree biomass. At $60 per dry ton, about 135 million dry tons of woody biomass consisting of hardwoods and mixed woods are harvested in south region, and softwoods are harvested in south and west regions. Further, increasing the price to $80 per dry ton, estimated available woody biomass is 254 million dry tons of hardwood harvested in the north and south regions, softwoods from south and west regions and mixed woods in the south.

Prominent differences between the land availability, acres regenerated and woody biomass supply in ½-mile and 1-mile road distance limits

Increasing land available for harvest from ½-mile to 1-mile road distance provides an additional 60.9 million acres (Figure 8). In 2020, at $40 per dry ton, both the ½-mile and 1-mile

road distance scenarios included 4.34 million acres available providing an estimated 21 million dry tons of woody biomass. At this price, most (90%) of the biomass are logging residues (Table 6). However, when prices increased to $60 per dry ton, the 1-mile scenario the potential biomass supply reached 112 million dry tons mostly (86%) from whole-tree biomass. This is about 21% higher biomass supply compared to the ½-mile road harvest distance. At $80 per dry ton, about 93% of biomass supply are from whole-tree biomass. This suggests that small diameter woody biomass is important source of feedstock if demand for cellulosic bioenergy is high. While both scenarios provided significant volume of woody biomass, over time, supply of woody biomass declines due to model restrictions. In 2020-2040, the ½-mile scenario available acres for harvest declines from 354.51 million acres to 302.4 million acres while acres under regeneration increases from 30.5 million acres to 82.6 million acres (Figure 8). This explains the reduction of timber and woody biomass productivity as more timberlands are under regeneration and reduce the acres available for harvest. However, in 2045-2055, timberland acres in the ½-mile scenario are no longer available for harvest and stands are assumed under regeneration. Similarly, the 1-mile road distance scenario available acres for harvest is also declining while acres in regeneration is increasing. For instance, in 2020, about 45.8 million acres are under regeneration and continue to increase until 2050 (133 million acres) and thereafter started to decline to 99.7 million acres in 2055. The decline in regenerated acres implies that in succeeding years more timberland acres available for harvest and more biomass feedstock available at lower price in 2055.

Discussion and Conclusion

The Energy Independence and Security Act of 2007 mandated an increase use of cellulosic biofuels under the expanded Renewable Fuel Standards. Forest logging residues

harvested along with the conventional timber products are potential feedstocks for cellulosic bioenergy. Recently, technologies in cellulosic biofuel production have improved the efficiency of converting woody biomass to biofuels. Developing this sector would provide additional opportunity to rural economies and forest landowners. This study can provide landowners, foresters, investors, policy makers and government agencies the scale of potential cellulosic feedstock woody residues to bioenergy sector development. This chapter presents the simulation of biomass supply curves under varying marginal prices in 2020 through 2055. Data were obtained from the US-Forest Service Forest Inventory Analysis database and were aggregated at the county level. The Forest Sustainable and Economic Analysis Model (ForSEAM) was used to estimate the feedstock supply to meet demands subject to timberland availability and harvest intensity, proportion of clearcut and thinning, growth and inter-period class diameter determination, conventional timber demand and woody biomass targets. Two baseline scenarios were used. The baseline scenario assumes moderate demand on conventional timber products and low demand for bioenergy. Under the scenario, one assumes that with moderate timber products demand, less of logging residues and more whole-tree biomass are available. Solutions to the model are solved in two steps. In the first simulation, timber growth and woody biomass supply target constraints were excluded in the model structure. However, the resulting optimal values of acres harvested in both conventional timber and cut-to-length options are used to change the RHS of the growth constraints. Next, the model solves the objective function using all the specified constraints. Woody biomass target is varied from 1 million dry tons to 300 million dry tons at 1-million dry ton increments to simulate the shadow values and to plot woody biomass supply curves overtime. South region plays a vital role in bioenergy development where most of the woody biomass supply are located. As with any other commodity, the development

of cellulosic biofuels and availability of woody biomass feedstock is based on costs and prices. At a price $40-$80 per dry ton, supply of woody biomass varies from 21 to 250 million dry tons.

The 2016 BTS uses ForSEAM in estimating the potential woody biomass from 2015 through 2040. In this study, ForSEAM is modified by increasing the modeling period up to from 2020-2055 and expand the timberland acres harvested up to 1-mile distance. Relaxing the model to extend up to 1-mile road harvest distance and increase the number of simulation years provided impact on the marginal costs and supply of woody biomass feedstock. Potential acres available for harvest increased an additional 60.9 million acres. At the onset, potential woody biomass feedstock supply is high and gradually declines over time because of the sustainability issues. For instance, a) building of temporary roads that may affect streams and water quality, soil erosion, wildlife habitat, and refuge, b) model restricts harvest limit to five percent relative to the timber growth rate. Thus, cannot harvest more than the growth rather previously harvested acres are allowed to grow and regenerate until it become class 2, c) cable system are assumed appropriate harvesting method in areas greater than 40% slope to prevent soil erosion and damage to forest floor and the model specified that no residues are collected in areas greater than 40% slope.

Over time, the marginal cost of producing an extra ton increased significantly so that it may no longer be feasible to produce. The harvestable timberlands decreased because of the restrictions in the model such as no conversion of forest cover and that natural pines are not converted to plantation management. Comparing the results of this study with that of the 2016 BTS, at $60 per dry ton, potential woody biomass feedstock supply doubled. This volume could have significant contribution in the overall goal of cellulosic biofuels under expanded Renewable Fuel Standards.

The added pressure placed on the nation's forests result in decreasing availability of mature timber in future years. While harvested acres are regenerating, the forests are becoming younger over time. The findings suggest that a government policy that incentivises the use of improved technology on tree genomics to increase tree productivity and hasten stand age maturity maybe needed as we increase the demand placed on out forests. Likewise, policies that increases the training of biomass feedstock specialists and strengthens extension activities to educate timberland owners on the importance of forest woody biomass in the development of bioenergy program would increase the amount of biomass available.

There are several important limitations in this study. Results are based on a set of assumptions embedded in the model. First, the acres harvested are fixed during the simulation period. Tracking timber acres harvested and stand regeneration over time can be an important modification in the model to increase the accuracy of findings. Second, the model assumed that no changes in forest cover and that harvested acres will re-establish to its original cover, and no conversion of natural pines to plantation management. This scenario has resulted to the decline of available harvested timberlands over time. When wood biomass energy demand increases, profit-driven forest landowners may convert natural pines to plantation management to cope with the demand and increase income. Third, the transaction costs embedded in the model are calculated at the roadside and do not cover transportation to the biorefinery or blending facilities. The estimates in POLYSYS do not site facilities and the distance to travel is unknown, therefore, transportation cost cannot be calculated. Moreover, the model did not include costs of establishing temporary road network because it is difficult to locate where the roads are going to be built. If, for instance, the costs of stumpage, cut, and haul doubled to account for the road

building cost, it is also not certain how much impact extending the harvest distance to one mile would have on the volume of potential woody biomass supply.

Future directions should include relaxing other assumptions such as allowing conversion of some natural pines to plantation pines and include transport cost from the roadside to facility to determine feedstock delivery least cost combination and site potential biorefinery location. Improve the regeneration module to better track the land and alter yields of that land as the land moves from supplying wood through regeneration. Further, integrating ForSEAM and POLYSYS models to determine simultaneously changes in land use in agricultural and forestland cover.

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Appendix

Table 1. Acres harvested for biomass by scenario, ownership, year, region, and cost per dry ton (private and public) in the U.S., 2020-2055

Region	Year	Marginal Cost ($/dry ton)	ML Scenario: 1-Mile Road Distance (Million Acres)				ML Scenario: ½-Mile Road Distance (Million Acres)			
			Logging Residues		Whole-Tree Biomass		Logging Residues		Whole-Tree Biomass	
			P[a]	F[a]	P[a]	F[a]	P[a]	F[a]	P[a]	F[a]
North	2020	40	0.8	0.2	0.0	0.0	0.8	0.2	0.0	0.0
	2020	60	0.8	0.2	1.2	0.5	0.8	0.2	1.0	0.3
	2020	80	0.5	0.1	3.2	1.0	0.5	0.1	2.8	0.7
	2025	40	0.7	0.2	0.0	0.0	0.7	0.2	0.0	0.0
	2025	60	0.8	0.2	1.0	0.4	0.7	0.2	0.8	0.3
	2025	80	0.5	0.1	3.0	0.9	0.5	0.1	2.5	0.7
	2030	40	0.8	0.2	0.0	0.0	0.7	0.2	0.0	0.0
	2030	60	0.7	0.2	0.7	0.4	0.7	0.2	0.6	0.2
	2030	80	0.5	0.1	2.5	0.8	0.5	0.1	2.2	0.6
	2035	40	0.7	0.2	0.0	0.0	0.6	0.2	0.0	0.0
	2035	60	0.7	0.2	0.2	0.2	0.7	0.2	0.1	0.1
	2035	80	0.5	0.1	1.6	0.7	0.5	0.1	1.4	0.5
	2040	40	0.6	0.2	0.0	0.0	0.6	0.2	0.0	0.0
	2040	60	0.6	0.2	0.2	0.2	0.6	0.2	0.1	0.1
	2040	80	0.4	0.1	1.1	0.5	0.4	0.1	1.0	0.3
	2045	40	0.5	0.2	0.0	0.0	0.0	0.0	0.0	0.0
	2045	60	0.5	0.2	0.1	0.1	0.0	0.0	0.0	0.0
	2045	80	0.4	0.1	0.5	0.2	0.0	0.0	0.0	0.0
	2050	40	0.4	0.2	0.0	0.0	0.0	0.0	0.0	0.0
	2050	60	0.4	0.2	0.0	0.0	0.0	0.0	0.0	0.0
	2050	80	0.4	0.1	0.3	0.2	0.0	0.0	0.0	0.0
	2055	40	0.5	0.2	0.0	0.0	0.0	0.0	0.0	0.0
	2055	60	0.5	0.2	0.0	0.0	0.0	0.0	0.0	0.0
	2055	80	0.4	0.1	0.3	0.1	0.0	0.0	0.0	0.0

[a] P-Private; F-Public

Table 1. Continued

Region	Year	Marginal Cost ($/dry ton)	ML Scenario: 1-Mile Road Distance (Million Acres)				ML Scenario: ½-Mile Road Distance (Million Acres)			
			Logging Residues		Whole-Tree Biomass		Logging Residues		Whole-Tree Biomass	
			P[a]	F[a]	P[a]	F[a]	P[a]	F[a]	P[a]	F[a]
South	2020	40	2.4	0.1	0.3	0.1	2.4	0.1	0.3	0.0
	2020	60	2.6	0.1	2.7	0.4	2.6	0.1	2.2	0.3
	2020	80	1.5	0.1	4.5	0.4	1.5	0.1	4.0	0.4
	2025	40	2.2	0.1	0.1	0.0	2.2	0.1	0.1	0.0
	2025	60	2.3	0.1	1.6	1.6	2.3	0.1	1.3	0.2
	2025	80	1.5	0.1	3.1	0.4	1.5	0.1	2.8	0.3
	2030	40	2.0	0.1	0.1	0.0	2.0	0.1	0.1	0.0
	2030	60	2.1	0.1	1.2	1.2	2.1	0.1	1.0	0.1
	2030	80	1.5	0.1	2.3	0.3	1.5	0.1	2.0	0.2
	2035	40	0.1	0.0	0.1	0.0	1.9	0.1	0.1	0.0
	2035	60	1.9	0.1	0.7	0.1	1.9	0.1	0.6	0.1
	2035	80	1.5	0.1	1.6	0.2	1.5	0.1	1.4	0.2
	2040	40	1.7	0.1	0.1	0.0	1.7	0.1	0.0	0.0
	2040	60	1.7	0.1	0.2	0.2	1.7	0.1	0.1	0.0
	2040	80	1.4	0.1	1.0	0.1	1.4	0.1	0.9	0.1
	2045	40	1.6	0.1	0.0	0.0	0.0	0.0	0.0	0.0
	2045	60	1.6	0.1	0.1	0.0	0.0	0.0	0.0	0.0
	2045	80	1.4	0.1	0.9	0.1	0.0	0.0	0.0	0.0
	2050	40	1.5	0.1	0.0	0.0	0.0	0.0	0.0	0.0
	2050	60	1.5	0.1	0.2	0.0	0.0	0.0	0.0	0.0
	2050	80	1.3	0.1	0.9	0.1	0.0	0.0	0.0	0.0
	2055	40	1.4	0.1	0.0	0.0	0.0	0.0	0.0	0.0
	2055	60	1.4	0.1	0.4	0.0	0.0	0.0	0.0	0.0
	2055	80	0.4	0.1	1.0	0.0	0.0	0.0	0.0	0.0

Table 1. Continued

Region	Year	Marginal Cost ($/dry ton)	ML Scenario: 1-Mile Road Distance (Million Acres)				ML Scenario: ½-Mile Road Distance (Million Acres)			
			Logging Residues		Whole-Tree Biomass		Logging Residues		Whole-Tree Biomass	
			P[a]	F[a]	P[a]	F[a]	P[a]	F[a]	P[a]	F[a]
West	2020	40	0.3	0.2	0.0	0.0	0.3	0.2	0.0	0.0
	2020	60	0.3	0.2	0.6	0.7	0.3	0.2	0.6	0.5
	2020	80	0.3	0.2	0.8	0.7	0.3	0.2	0.7	0.6
	2025	40	0.3	0.2	0.0	0.0	0.3	0.2	0.0	0.0
	2025	60	0.3	0.2	0.4	0.6	0.3	0.2	0.4	0.4
	2025	80	0.3	0.2	0.6	0.7	0.3	0.2	0.5	0.5
	2030	40	0.3	0.2	0.0	0.0	0.3	0.2	0.0	0.0
	2030	60	0.4	0.2	0.4	0.4	0.3	0.2	0.3	0.4
	2030	80	0.3	0.2	0.5	0.7	0.3	0.2	0.4	0.5
	2035	40	0.3	0.2	0.0	0.0	0.3	0.2	0.0	0.0
	2035	60	0.3	0.2	0.4	0.6	0.3	0.2	0.3	0.4
	2035	80	0.3	0.2	0.5	0.7	0.3	0.2	0.4	0.5
	2040	40	0.3	0.2	0.0	0.0	0.3	0.2	0.0	0.0
	2040	60	0.3	0.3	0.4	0.6	0.3	0.2	0.3	0.4
	2040	80	0.3	0.2	0.4	0.6	0.3	0.2	0.3	0.4
	2045	40	0.3	0.2	0.0	0.0	0.0	0.0	0.0	0.0
	2045	60	0.3	0.2	0.3	0.4	0.0	0.0	0.0	0.0
	2045	80	0.3	0.2	0.3	0.5	0.0	0.0	0.0	0.0
	2050	40	0.3	0.2	0.0	0.0	0.0	0.0	0.0	0.0
	2050	60	0.4	0.2	0.3	0.4	0.0	0.0	0.0	0.0
	2050	80	0.3	0.2	0.3	0.5	0.0	0.0	0.0	0.0
	2055	40	0.3	0.2	0.0	0.0	0.0	0.0	0.0	0.0
	2055	60	0.3	0.2	0.3	0.3	0.0	0.0	0.0	0.0
	2055	80	0.3	0.2	0.4	0.3	0.0	0.0	0.0	0.0

Table 2. Acres harvested for biomass in private timberlands by scenario, region, year, feedstock type and stand diameter and ownership at $60 per dry in the U.S., 2020-2055

			Logging Residues			Whole-Tree Biomass					
			Class 1 Stand	Class 2 Stand		Class 2 Stand		Class 3 stand		Total	
Scenario	Region	Year	CC	CC	T	CC	T	CC	T	CC	T
			(million acres)								
ML scenario: 1-Mile Road Distance	North	2020	0.2	0.1	0.5	0.0	0.2	0.9	0.0	1.2	0.8
		2025	0.2	0.1	0.5	0.0	0.2	0.7	0.0	1.0	0.7
		2030	0.2	0.1	0.4	0.0	0.3	0.4	0.0	0.7	0.8
		2035	0.2	0.1	0.4	0.0	0.1	0.1	0.0	0.3	0.5
		2040	0.2	0.0	0.3	0.0	0.1	0.0	0.0	0.3	0.4
		2045	0.3	0.0	0.2	0.0	0.0	0.0	0.0	0.3	0.2
		2050	0.3	0.0	0.2	0.0	0.0	0.0	0.0	0.3	0.2
		2055	0.3	0.0	0.2	0.0	0.0	0.0	0.0	0.3	0.2
	South	2020	0.7	0.0	1.8	1.0	0.8	0.8	0.0	2.6	2.7
		2025	0.8	0.0	1.5	0.7	0.5	0.4	0.0	2.0	2.0
		2030	1.0	0.1	1.0	0.5	0.5	0.2	0.0	1.8	1.5
		2035	1.0	0.1	0.8	0.3	0.3	0.1	0.0	1.6	1.1
		2040	1.0	0.1	0.6	0.1	0.1	0.1	0.0	1.3	0.7
		2045	0.8	0.2	0.6	0.0	0.0	0.1	0.0	1.1	0.6
		2050	0.8	0.1	0.6	0.2	0.0	0.0	0.0	1.1	0.6
		2055	0.8	0.0	0.6	0.3	0.1	0.0	0.0	1.1	0.7
	West	2020	0.3	0.0	0.0	0.3	0.3	0.0	0.0	0.6	0.4
		2025	0.3	0.0	0.0	0.2	0.2	0.0	0.0	0.5	0.2
		2030	0.3	0.0	0.0	0.2	0.2	0.0	0.0	0.5	0.2
		2035	0.3	0.0	0.0	0.2	0.2	0.0	0.0	0.5	0.2
		2040	0.3	0.0	0.0	0.2	0.2	0.0	0.0	0.5	0.2
		2045	0.3	0.0	0.0	0.1	0.1	0.0	0.0	0.4	0.2
		2050	0.3	0.0	0.0	0.1	0.1	0.0	0.0	0.4	0.2
		2055	0.3	0.0	0.0	0.1	0.2	0.0	0.0	0.4	0.2

CC-clearcut; T-thinning

Table 2. Continued

Scenario	Region	Year	Logging Residues			Whole-Tree biomass				Total	
			Class 1 Stand	Class 2 Stand		Class 2 Stand		Class 3 stand			
			CC	CC	T	CC	T	CC	T	CC	T
						(million acres)					
ML Scenario: ½-Mile Road Distance	North	2020	0.3	0.1	0.7	0.0	0.3	1.0	0.0	1.4	0.9
		2025	0.3	0.1	0.6	0.0	0.2	0.9	0.0	1.2	0.8
		2030	0.3	0.1	0.5	0.0	0.3	0.5	0.0	0.9	0.8
		2035	0.3	0.1	0.5	0.0	0.1	0.1	0.0	0.5	0.6
		2040	0.3	0.0	0.4	0.0	0.1	0.0	0.0	0.4	0.5
		2045	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		2050	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		2055	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	South	2020	0.3	0.1	0.7	1.0	0.7	0.8	0.0	2.1	1.4
		2025	0.9	0.0	1.5	0.7	0.5	0.4	0.0	2.0	1.9
		2030	1.1	0.1	1.0	0.5	0.4	0.2	0.0	1.8	1.5
		2035	1.1	0.1	0.8	0.3	0.3	0.1	0.0	1.6	1.0
		2040	1.0	0.1	0.6	0.1	0.0	0.1	0.0	1.3	0.7
		2045	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		2050	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		2055	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	West	2020	0.5	0.0	0.0	0.4	0.6	0.0	0.0	1.0	0.6
		2025	0.5	0.0	0.0	0.3	0.4	0.0	0.0	0.9	0.5
		2030	0.5	0.0	0.0	0.3	0.4	0.0	0.0	0.9	0.5
		2035	0.5	0.0	0.0	0.3	0.4	0.0	0.0	0.8	0.5
		2040	0.5	0.0	0.0	0.3	0.4	0.0	0.0	0.8	0.4
		2045	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		2050	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		2055	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

CC-clearcut; T-thinning

Table 3. Acres harvested for biomass in public timberlands by scenario, region, year, feedstock type, stand diameter and ownership at $60 per dry ton in the U.S., 2020-2055

Scenario	Region	Year	Logging Residues			Whole-Tree biomass				Total	
			Class 1 Stand	Class 2 Stand		Class 2 Stand		Class 3 stand			
			CC	CC	T	CC	T	CC	T	CC	T
			(million acres)								
ML scenario: 1-Mile Road Distance	North	2020	0.1	0.0	0.1	0.0	0.1	0.3	0.0	0.4	0.3
		2025	0.1	0.0	0.1	0.0	0.1	0.3	0.0	0.4	0.3
		2030	0.1	0.0	0.1	0.0	0.1	0.2	0.0	0.3	0.2
		2035	0.1	0.0	0.1	0.0	0.1	0.1	0.0	0.2	0.2
		2040	0.1	0.0	0.1	0.0	0.1	0.0	0.0	0.1	0.2
		2045	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.1	0.1
		2050	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.1	0.1
		2055	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.1	0.1
	South	2020	0.0	0.0	0.1	0.1	0.2	0.1	0.0	0.2	0.3
		2025	0.0	0.0	0.1	0.7	0.5	0.4	0.0	1.1	0.6
		2030	0.0	0.0	0.1	0.5	0.5	0.2	0.0	0.7	0.6
		2035	0.0	0.0	0.1	0.0	0.1	0.0	0.0	0.1	0.1
		2040	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1
		2045	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1
		2050	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0
		2055	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	West	2020	0.2	0.0	0.0	0.3	0.4	0.0	0.0	0.5	0.4
		2025	0.2	0.0	0.0	0.2	0.3	0.0	0.0	0.4	0.3
		2030	0.2	0.0	0.0	0.2	0.3	0.0	0.0	0.4	0.3
		2035	0.2	0.0	0.0	0.2	0.3	0.0	0.0	0.4	0.3
		2040	0.3	0.0	0.0	0.2	0.3	0.0	0.0	0.6	0.3
		2045	0.2	0.0	0.0	0.2	0.2	0.0	0.0	0.4	0.3
		2050	0.2	0.0	0.0	0.2	0.2	0.0	0.0	0.4	0.2
		2055	0.2	0.0	0.0	0.1	0.2	0.0	0.0	0.3	0.2

CC-clearcut; T-thinning

Table 3. Continued

Scenario	Region	Year	Logging Residues			Whole-Tree biomass				Total	
			Class 1 Stand	Class 2 Stand		Class 2 Stand		Class 3 stand			
			CC	CC	T	CC	T	CC	T	CC	T
			(million acres)								
ML scenario: ½-Mile Road Distance	North	2020	0.1	0.0	0.1	0.0	0.1	0.3	0.0	0.3	0.2
		2025	0.1	0.0	0.1	0.0	0.1	0.2	0.0	0.3	0.2
		2030	0.1	0.0	0.1	0.0	0.1	0.2	0.0	0.3	0.2
		2035	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.1	0.2
		2040	0.1	0.0	0.1	0.0	0.1	0.0	0.0	0.1	0.2
		2045	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		2050	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		2055	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	South	2020	0.0	0.0	0.1	0.1	0.1	0.1	0.0	0.2	0.2
		2025	0.0	0.0	0.1	0.1	0.1	0.0	0.0	0.1	0.2
		2030	0.0	0.0	0.1	0.0	0.1	0.0	0.0	0.1	0.1
		2035	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.1	0.1
		2040	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0
		2045	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		2050	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		2055	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	West	2020	0.2	0.0	0.0	0.2	0.3	0.0	0.0	0.4	0.3
		2025	0.2	0.0	0.0	0.2	0.2	0.0	0.0	0.4	0.3
		2030	0.2	0.0	0.0	0.2	0.2	0.0	0.0	0.4	0.3
		2035	0.2	0.0	0.0	0.2	0.2	0.0	0.0	0.4	0.3
		2040	0.2	0.0	0.0	0.2	0.2	0.0	0.0	0.4	0.2
		2045	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		2050	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		2055	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

CC-clearcut; T-thinning

Table 4. Woody biomass supply in private timberlands by scenario, region, year, feedstock and stand type at $60 per dry ton in the U.S., 2020-2055

Scenario	Region	Year	Logging Residues			Whole-Tree biomass				Total	
			Class 1 Stand	Class 2 Stand		Class 2 Stand		Class 3 stand			
			CC	CC	T	CC	T	CC	T	CC	T
			(million dry tons)								
ML Scenario: 1-Mile Road Distance	North	2020	1.6	0.3	1.9	0.6	4.8	7.1	0.0	9.6	6.7
		2025	1.7	0.3	1.9	0.5	4.8	6.9	0.0	9.5	6.7
		2030	1.8	0.4	1.8	0.7	8.3	3.3	0.0	6.2	10.1
		2035	1.8	0.3	1.9	0.3	2.5	0.6	0.0	3.0	4.4
		2040	2.3	0.2	1.4	0.3	3.2	0.2	0.0	3.0	4.5
		2045	2.5	0.1	1.0	0.1	0.7	0.2	0.0	3.0	1.7
		2050	2.6	0.1	1.0	0.1	0.7	0.0	0.0	2.9	1.7
		2055	2.7	0.1	1.1	0.1	0.6	0.1	0.0	3.0	1.7
	South	2020	5.1	0.1	5.8	36.1	20.1	5.5	0.0	46.8	25.9
		2025	6.1	0.1	5.6	28.9	13.6	2.6	0.0	37.7	19.2
		2030	7.8	0.4	4.4	20.7	14.7	1.4	0.0	30.3	19.1
		2035	8.5	0.7	3.9	14.2	11.0	1.2	0.0	24.5	14.9
		2040	8.1	1.0	3.8	6.5	1.9	6.5	0.0	22.2	5.7
		2045	7.4	1.5	4.0	3.1	0.1	0.9	0.0	12.8	4.1
		2050	7.6	0.7	4.5	13.0	0.5	0.7	0.0	22.0	5.0
		2055	7.8	0.3	4.7	21.0	8.9	0.7	0.0	29.7	13.6
	West	2020	1.9	0.0	0.0	7.2	5.4	0.1	0.0	9.3	5.4
		2025	2.1	0.0	0.0	4.7	3.5	0.2	0.0	6.9	3.6
		2030	2.2	0.0	0.1	5.2	3.7	0.1	0.0	7.5	3.8
		2035	2.3	0.0	0.1	4.9	3.5	0.1	0.0	7.3	3.7
		2040	2.4	0.0	0.1	4.2	3.6	0.1	0.0	6.7	3.7
		2045	2.4	0.0	0.1	3.5	3.1	0.0	0.0	6.0	3.2
		2050	2.5	0.0	0.1	4.1	3.4	0.0	0.0	6.6	3.6
		2055	2.1	0.0	0.2	4.4	3.5	0.0	0.0	6.6	3.6

CC-clearcut; T-thinning

Table 4. Continued

Scenario	Region	Year	Logging Residues			Whole-Tree biomass				Total	
			Class 1 Stand	Class 2 Stand		Class 2 Stand		Class 3 stand			
			CC	CC	T	CC	T	CC	T	CC	T
			(million dry tons)								
ML Scenario: ½-Mile Road Distance	North	2020	0.3	0.1	0.7	0.7	5.1	7.8	0.0	8.8	5.8
		2025	2.2	0.4	2.4	0.7	4.9	7.5	0.0	10.8	7.3
		2030	2.3	0.4	2.4	0.7	7.0	4.4	0.0	7.9	9.4
		2035	2.3	0.4	2.4	0.5	2.8	0.8	0.0	4.0	5.2
		2040	2.5	0.3	2.1	0.6	3.8	0.3	0.0	3.7	5.9
		2045	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		2050	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		2055	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	South	2020	0.8	0.0	1.9	34.7	16.3	5.3	0.0	40.7	18.2
		2025	6.5	0.2	5.6	28.0	12.2	2.5	0.0	37.1	17.8
		2030	8.2	0.4	4.5	19.8	12.7	1.3	0.0	29.8	17.1
		2035	8.9	0.7	4.0	13.4	9.1	1.1	0.0	24.1	13.1
		2040	8.6	1.1	3.8	5.5	0.9	0.7	0.0	15.9	4.7
		2045	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		2050	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		2055	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	West	2020	0.5	0.0	0.0	12.6	9.8	0.2	0.0	13.3	9.8
		2025	2.8	0.0	0.0	10.0	8.3	0.3	0.0	13.1	8.4
		2030	3.0	0.0	0.1	10.4	8.6	0.2	0.0	13.6	8.7
		2035	3.1	0.0	0.1	10.6	9.0	0.2	0.0	13.9	9.1
		2040	3.2	0.0	0.1	9.7	9.1	0.2	0.0	13.2	9.3
		2045	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		2050	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		2055	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

CC-clearcut; T-thinning

Table 5. Woody biomass supply in public timberlands by scenario, region, year, feedstock and stand type at $60 per dry ton in the U.S., 2020-2055

Scenario	Region	Year	Logging Residues			Whole-Tree biomass				Total	
			Class 1 Stand	Class 2 Stand		Class 2 Stand		Class 3 stand			
			CC	CC	T	CC	T	CC	T	CC	T
			(million dry tons)								
ML Scenario: 1-Mile Road Distance	North	2020	0.4	0.1	0.5	0.3	2.4	2.4	0.0	3.3	2.9
		2025	0.4	0.1	0.5	0.2	2.5	2.3	0.0	3.1	3.0
		2030	0.5	0.1	0.5	0.2	2.5	2.2	0.0	3.0	3.0
		2035	0.5	0.1	0.5	0.2	2.5	0.5	0.0	1.3	3.1
		2040	0.5	0.1	0.5	0.4	3.1	0.3	0.0	1.3	3.7
		2045	0.5	0.0	0.6	0.3	0.0	0.4	0.0	1.1	0.6
		2050	0.5	0.0	0.6	0.5	0.8	0.0	0.0	1.0	1.4
		2055	0.5	0.0	0.5	0.3	0.7	0.0	0.0	0.9	1.3
	South	2020	0.2	0.0	0.3	3.9	3.8	0.4	0.0	4.6	4.1
		2025	0.3	0.0	0.3	3.7	3.8	0.2	0.0	4.2	4.1
		2030	0.3	0.0	0.3	2.7	2.6	0.1	0.0	3.2	2.9
		2035	0.3	0.0	0.3	2.0	2.2	0.1	0.0	2.4	2.4
		2040	0.4	0.0	0.2	1.1	1.1	0.1	0.0	1.5	1.3
		2045	0.4	0.0	0.2	0.8	0.7	0.1	0.0	1.3	0.9
		2050	0.4	0.1	0.2	0.4	0.1	0.0	0.0	0.8	0.2
		2055	0.3	0.1	0.2	0.0	0.0	0.0	0.0	0.5	0.2
	West	2020	0.7	0.0	0.0	8.0	6.6	0.1	0.0	8.9	6.6
		2025	0.8	0.0	0.0	7.6	6.8	0.2	0.0	8.6	6.8
		2030	2.2	0.0	0.1	8.0	7.1	0.1	0.0	10.3	7.2
		2035	0.8	0.0	0.0	8.1	7.4	0.1	0.0	9.0	7.4
		2040	0.8	0.0	0.0	7.9	7.7	0.1	0.0	8.9	7.7
		2045	0.9	0.0	0.0	6.5	6.5	0.1	0.0	7.5	6.5
		2050	0.9	0.0	0.1	6.8	6.7	0.0	0.0	7.8	6.7
		2055	0.9	0.0	0.1	5.0	4.7	0.0	0.0	5.9	4.8

CC-clearcut; T-thinning

Table 5. Continued

Scenario	Region	Year	Logging Residues			Whole-Tree biomass				Total	
			Class 1 Stand	Class 2 Stand		Class 2 Stand		Class 3 stand			
			CC	CC	T	CC	T	CC	T	CC	T
			(million dry tons)								
ML Scenario: ½-Mile Road Distance	North	2020	0.5	0.2	0.5	0.2	2.5	2.4	0.0	3.2	3.0
		2025	0.5	0.2	0.6	0.2	2.5	2.0	0.0	2.8	3.1
		2030	0.5	0.2	0.6	0.2	2.4	1.4	0.0	2.2	3.0
		2035	0.5	0.1	0.6	0.2	2.2	0.2	0.0	1.0	2.8
		2040	0.5	0.1	0.5	0.3	1.8	0.1	0.0	1.0	2.4
		2045	0.6	0.1	0.4	0.0	0.0	0.1	0.0	0.7	0.4
		2050	0.7	0.0	0.3	0.0	0.0	0.0	0.0	0.7	0.3
		2055	0.7	0.0	0.3	0.0	0.0	0.0	0.0	0.7	0.3
	South	2020	0.3	0.0	0.3	3.9	3.9	0.3	0.0	4.4	4.1
		2025	0.3	0.0	0.2	3.6	4.0	0.1	0.0	4.0	4.2
		2030	0.3	0.0	0.2	2.6	2.8	0.1	0.0	3.0	3.0
		2035	0.3	0.0	0.2	1.6	2.0	0.0	0.0	2.0	2.2
		2040	0.3	0.0	0.2	0.7	0.5	0.0	0.0	1.1	0.6
		2045	0.3	0.1	0.2	0.4	0.1	0.0	0.0	0.8	0.3
		2050	0.3	0.1	0.2	0.2	0.0	0.0	0.0	0.6	0.2
		2055	0.3	0.0	0.2	0.5	0.0	0.0	0.0	0.8	0.2
	West	2020	0.7	0.0	0.0	8.1	6.6	0.1	0.0	9.0	6.6
		2025	0.8	0.0	0.0	7.6	6.8	0.1	0.0	8.5	6.8
		2030	0.8	0.0	0.0	7.1	6.4	0.1	0.0	7.9	6.4
		2035	0.8	0.0	0.0	5.3	4.7	0.0	0.0	6.1	4.7
		2040	0.8	0.0	0.0	3.4	3.3	0.0	0.0	4.3	3.3
		2045	0.8	0.0	0.0	2.1	2.0	0.0	0.0	3.0	2.0
		2050	0.8	0.0	0.0	1.6	1.5	0.0	0.0	2.5	1.5
		2055	0.9	0.0	0.0	1.1	0.9	0.0	0.0	2.0	0.9

CC-clearcut; T-thinning

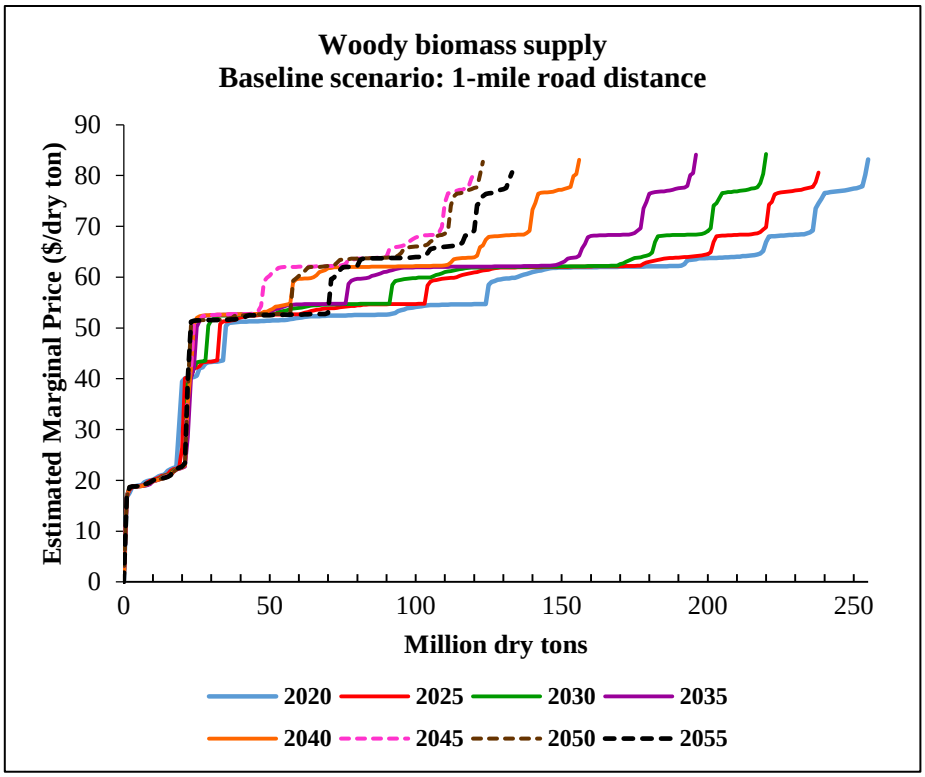
Table 6. Dry tons of woody biomass supplied by price, feedstock type, and scenario in the U.S., 2020-2055

Year		ML Scenario: 1-Mile Road Distance (Million dry tons)			ML Scenario: ½-Mile Road Distance (Million dry tons)		
	Marginal Cost ($/dry ton)	Logging residues	Whole-tree biomass	Total	Logging residues	Whole-tree biomass	Total
2020	40	19.1	1.9	21.0	19.0	2.0	21.0
2020	60	19.2	115.8	135.0	19.1	92.9	112.0
2020	80	17.8	236.2	254.0	17.7	203.3	221.0
2025	40	20.3	0.7	21.0	20.2	0.8	21.0
2025	60	20.3	93.7	114.0	20.3	74.7	95.0
2025	80	18.9	219.1	238.0	18.9	186.1	205.0
2030	40	21.5	0.5	22.0	21.5	0.5	22.0
2030	60	21.6	83.4	105.0	21.5	65.5	87.0
2030	80	20.2	198.8	219.0	20.2	167.8	188.0
2035	40	22.2	0.8	23.0	22.1	0.9	23.0
2035	60	22.3	61.7	84.0	22.2	47.8	70.0
2035	80	21.0	173.0	194.0	21.0	146.0	167.0
2040	40	22.0	1.0	23.0	21.9	0.0	21.9
2040	60	22.0	43.0	65.0	21.9	31.1	53.0
2040	80	21.0	133.0	154.0	20.9	112.1	133.0
2045	40	21.9	0.1	22.0	0.0	0.0	0.0
2045	60	21.9	27.1	49.0	0.0	0.0	0.0
2045	80	21.0	99.0	120.0	0.0	0.0	0.0
2050	40	22.0	0.0	22.0	0.0	0.0	0.0
2050	60	22.0	37.0	59.0	0.0	0.0	0.0
2050	80	21.2	100.8	122.0	0.0	0.0	0.0
2055	40	21.8	0.2	22.0	0.0	0.0	0.0
2055	60	21.8	50.2	72.0	0.0	0.0	0.0
2055	80	20.8	112.2	133.0	0.0	0.0	0.0

Table 7. Timberland acres included in the model by region, class, slope, ownership and stand type in 1-mile road harvest distance in the U.S.

	Class	Slope	Ownership	LHW	UHW	NP	PP	Mixed	Total
				Million acres					
North	1	LE40	Private	23.7	32.3	6.3	0.7	2.4	65.3
			Public	5.5	7.0	2.2	0.9	0.7	16.3
		GT40	Private	1.9	4.5	0.2	0.0	0.2	6.7
			Public	0.5	0.7	0.0	0.0	0.0	1.2
	2	LE40	Private	12.9	14.1	3.9	0.6	1.1	32.6
			Public	2.5	4.3	1.6	0.3	0.3	9.0
		GT40	Private	0.3	0.7	0.0	0.0	0.1	1.1
			Public	0.1	0.2	0.0	0.0	0.0	0.3
	3	LE40	Private	5.7	7.5	3.6	0.2	0.4	17.4
			Public	1.1	3.0	1.5	0.2	0.2	6.0
		GT40	Private	0.1	0.2	0.0	0.0	0.0	0.4
			Public	0.0	0.0	0.0	0.0	0.0	0.0
South	1	LE40	Private	15.2	30.9	14.5	13.5	8.2	82.4
			Public	2.5	4.5	4.8	0.8	1.5	14.1
		GT40	Private	0.8	6.2	0.2	0.1	0.3	7.5
			Public	0.1	1.7	0.2	0.0	0.1	2.0
	2	LE40	Private	5.4	12.7	5.8	15.5	4.2	43.6
			Public	0.6	1.3	0.8	0.9	0.5	4.1
		GT40	Private	0.1	1.3	0.1	0.1	0.1	1.6
			Public	0.0	0.3	0.0	0.0	0.1	0.3
	3	LE40	Private	5.3	13.9	3.5	8.7	5.3	36.7
			Public	0.5	1.0	0.5	0.3	0.5	2.8
		GT40	Private	0.0	0.4	0.0	0.0	0.0	0.6
			Public	0.0	0.1	0.0	0.0	0.0	0.1
West	1	LE40	Private	2.1	1.8	12.6	1.8	0.0	18.3
			Public	0.5	0.9	25.1	1.3	0.0	27.8
		GT40	Private	0.4	0.9	4.1	0.7	0.0	6.1
			Public	0.3	0.6	11.5	0.8	0.0	13.2
	2	LE40	Private	0.8	1.4	1.7	0.9	0.1	4.9
			Public	0.2	1.0	3.4	0.4	0.0	5.1
		GT40	Private	0.2	0.4	0.6	0.4	0.0	1.6
			Public	0.1	0.5	1.1	0.2	0.0	1.9
	3	LE40	Private	0.7	0.7	2.9	1.4	0.0	5.7
			Public	0.2	0.8	3.8	0.4	0.0	5.1
		GT40	Private	0.2	0.2	0.7	0.5	0.0	1.5
			Public	0.1	0.3	1.1	0.2	0.0	1.8

LE40 - slope is less than 40; GT40 - slope is greater than 40



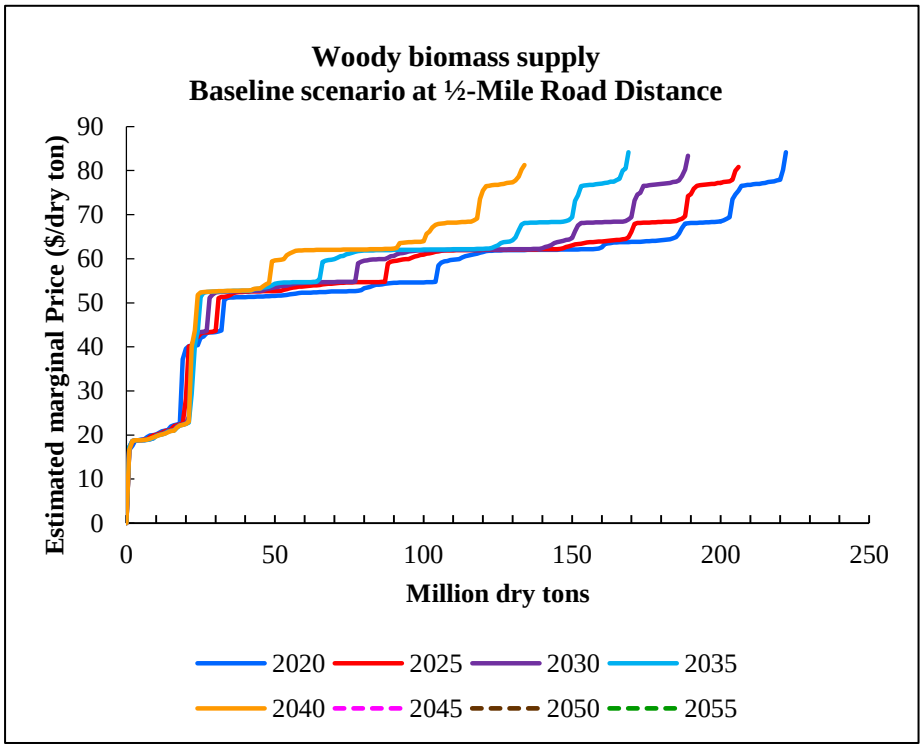


Figure 3. Woody biomass supply curves in the U.S., 2020-2055

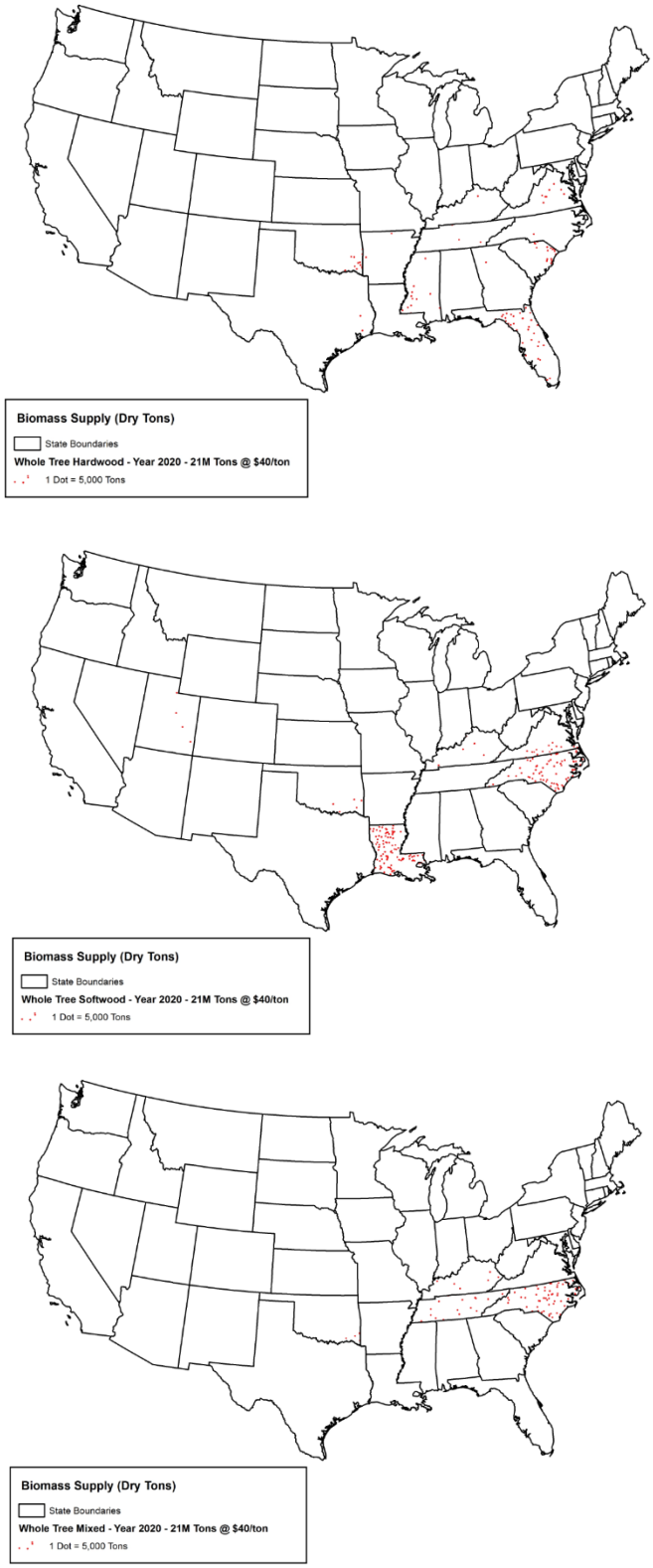


Figure 4. Supply of whole-tree woody biomass at $40 per dry ton by stand type, 2020

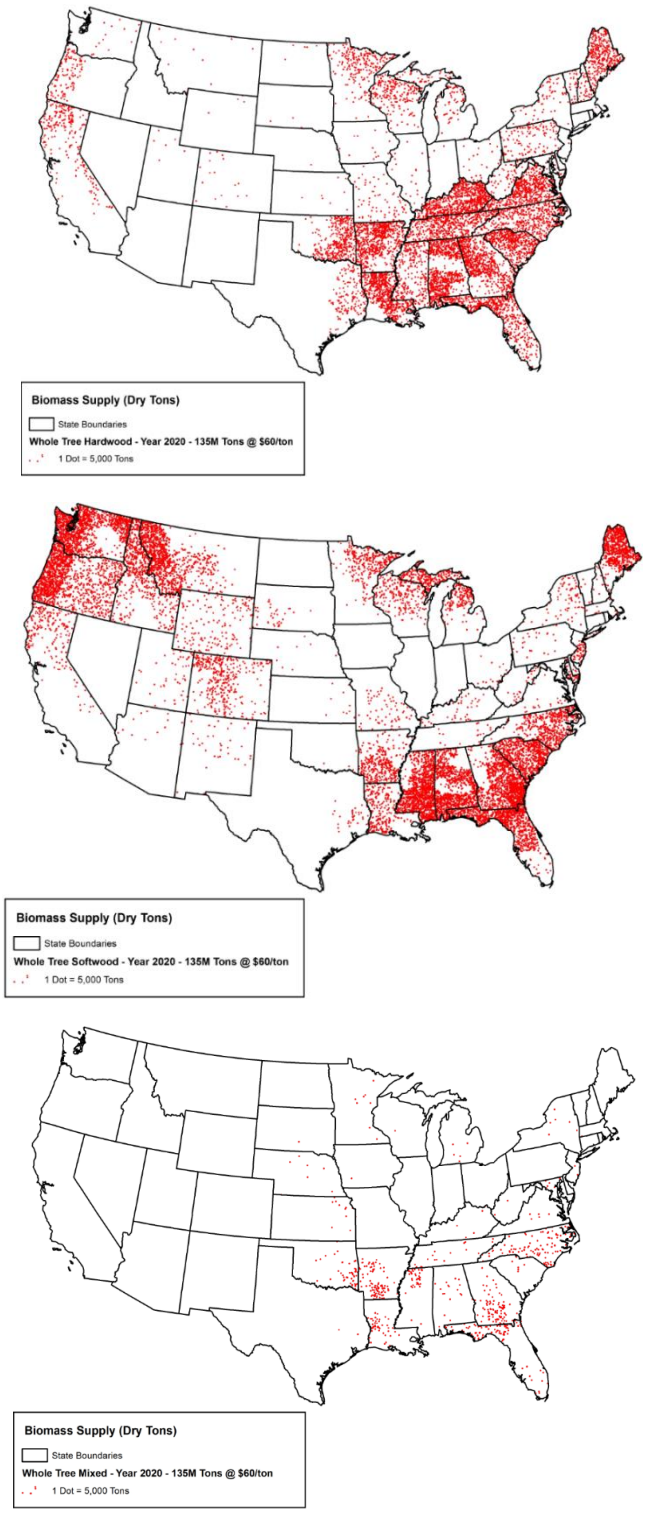


Figure 5. Supply of whole-tree woody biomass supply at $60 per dry ton by stand type, 2020

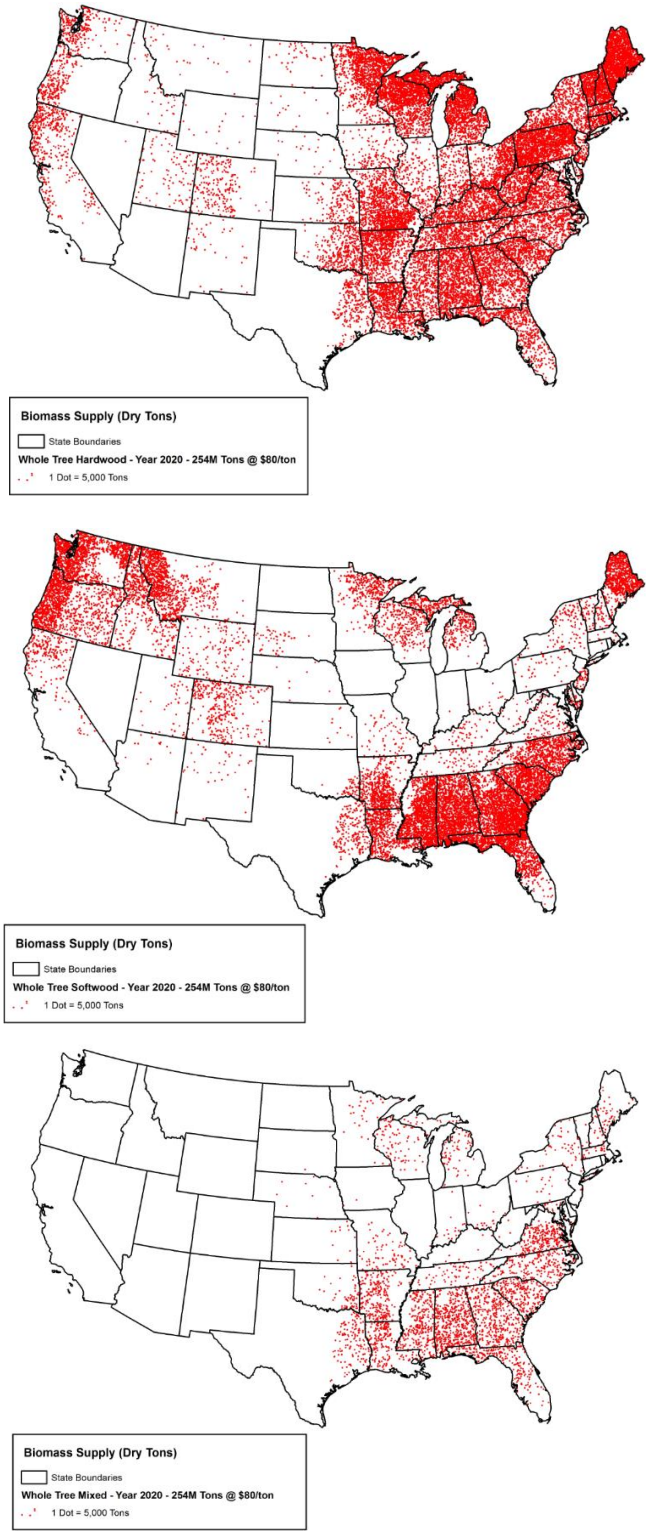


Figure 6. Supply of whole-tree biomass at $80 per dry ton by stand type, 2020

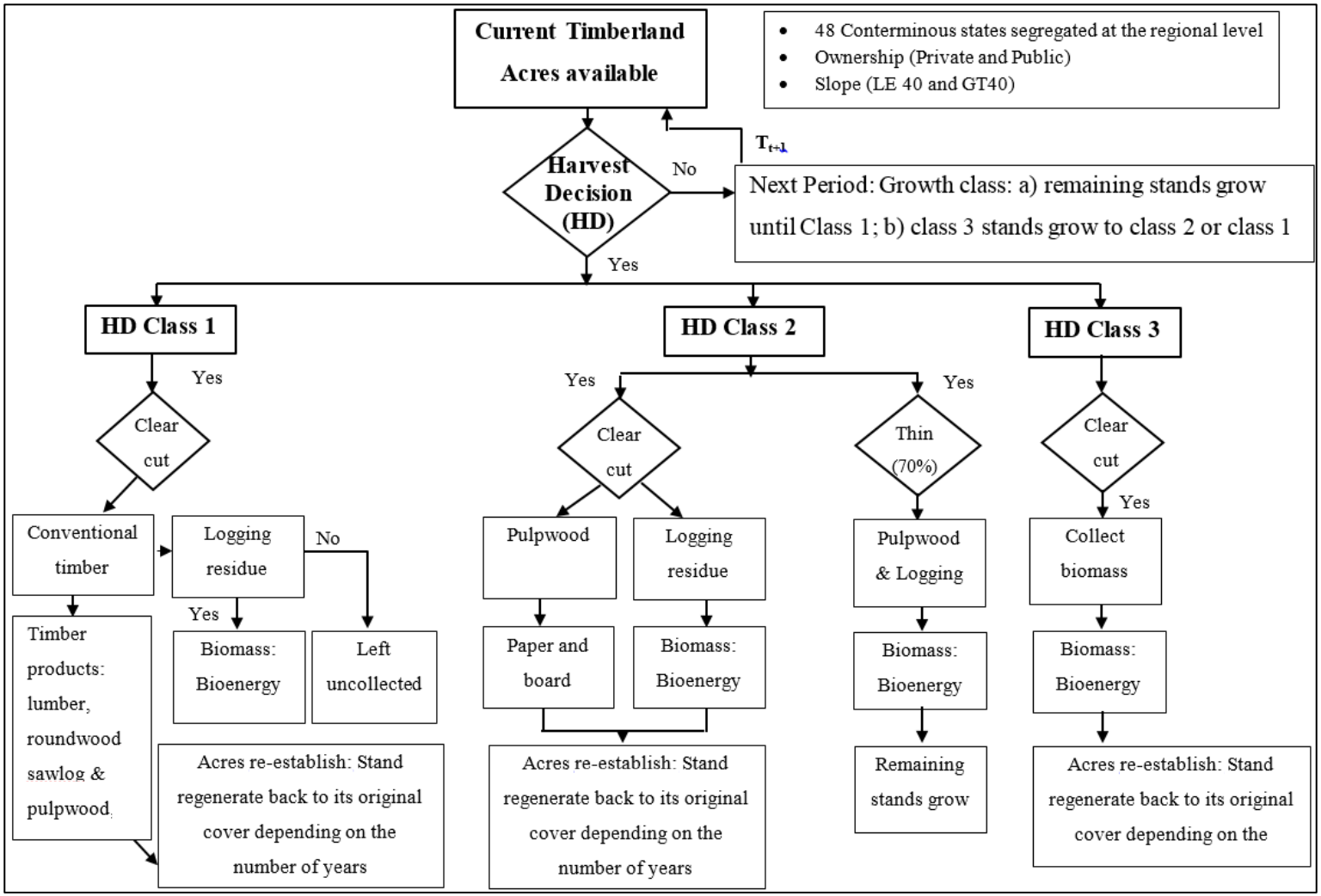
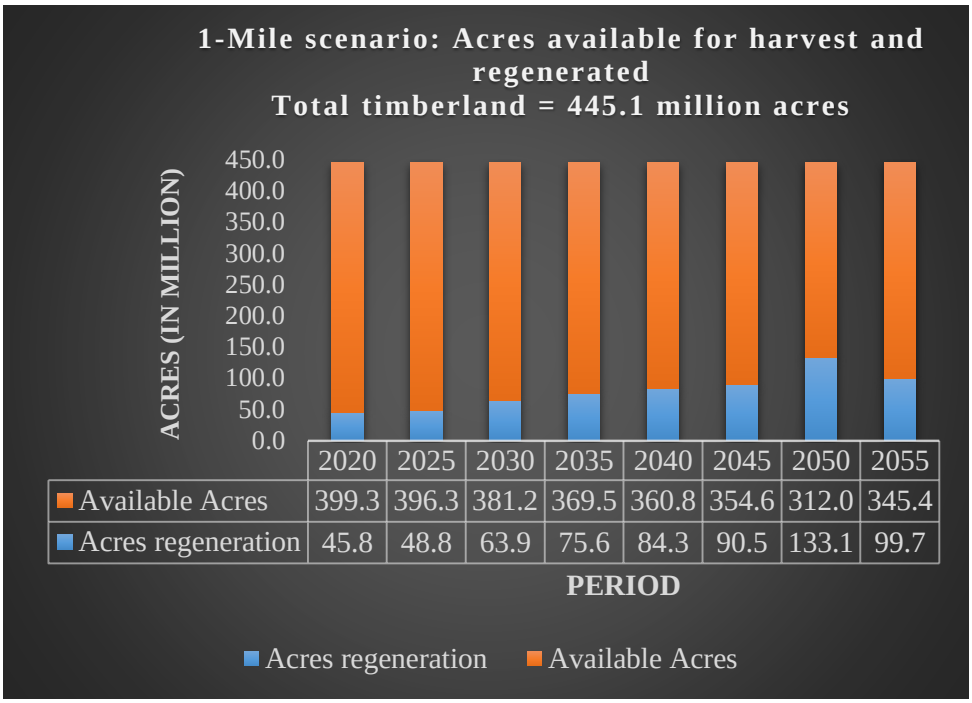


Figure 7. Forest Sustainable Economic Analysis Model (ForSEAM) Flow Chart



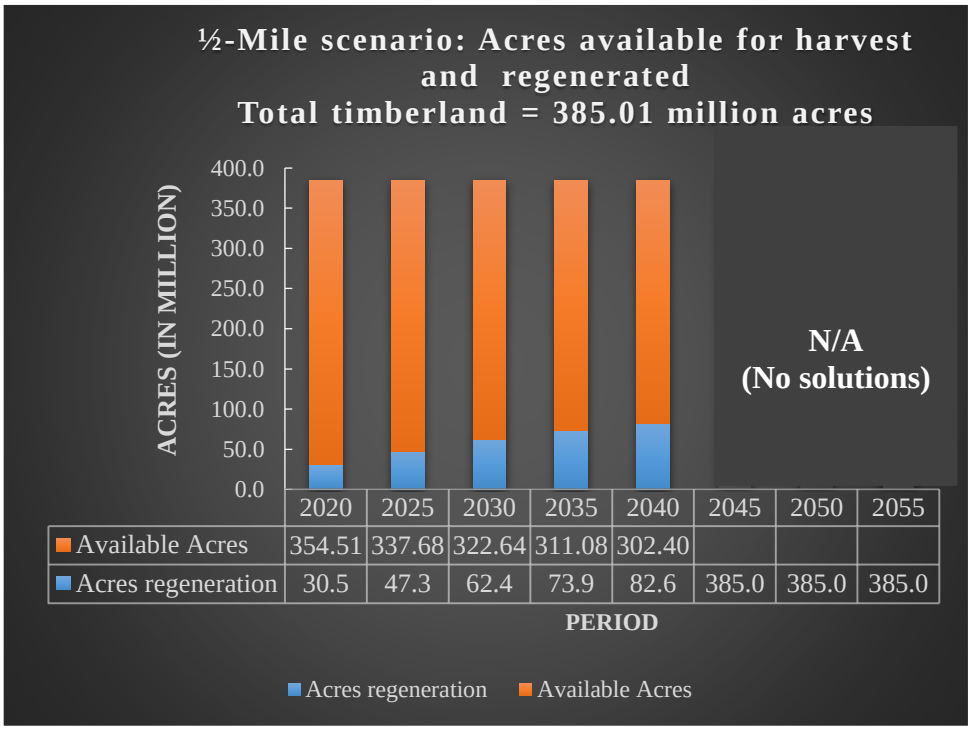


Figure 8. Timberland acres harvested and regenerated in the U.S.

Chapter III: Tracking Forest Growth and Acres Regeneration in the Forest Sustainable and Economic Analysis Model (ForSEAM)

Abstract

Forests are one of the largest carbon sinks, storing carbon as tree biomass. The forest could be a significant driver to mitigating the impact of greenhouse gases. Efficient forest management practices help maintain the balance between forest resource extraction and regeneration. Harvesting biomass from the forest should adhere to Best Management Practices as the harvest and collection can have environmental impacts especially on soil and water qualities. Cellulosic woody biomass consisting of forest logging residues and non-merchantable timber could be an important feedstock under the Energy Independence and Security Act of 2007. It has potential to provide large quantities of feedstock for bioenergy. This study provides estimates of the changes of U.S. timberlands over time and its ability to meet conventional timber products and bioenergy demand. ForSEAM, a linear cost minimization model simulates potential supply of woody biomass to meet conventional timber and bioenergy demand subject to various constraints. The model is modified to track annual changes of existing timberlands harvested, regenerated timberland, and acres of timberlands remaining for harvest. Two scenarios are examined over time. Scenario 1 assumes that existing stand growth and acreages do not vary, and scenario 2 assumes that stand growth and regeneration vary over the modeling period. An updated ForSEAM transition matrix is used to trace the annual changes of stand growth and existing timberlands. This table contains data on tree types, class stands, and number of years. This study covers the south region. The national forests and timberlands classified as reserved are also excluded due to statutory laws and regulations as well as environmental sustainability issues. Results show that available potential supply of woody biomass ranges from 5-90 million dry tons depending on prices. At lower prices, most of the biomass available are logging residues. In all periods, scenario 2 provides more potential woody biomass supply compared to

scenario 1. At $70 per dry ton, about 90 million dry tons are available in 2020 and 55 million dry tons in 2055, mostly coming from whole-tree biomass.

Introduction

In the U.S., the demand for woody biomass for bioenergy is increasing to meet the minimum required volume under Renewable Fuel Standards (RFS) program, technology advancement (He et al., 2016), and may expand economic opportunities (Schnepf and Yacobucci, 2010). Shifting reliance from petroleum to renewable resources leads to sustainable industrial development (FitzPatrick et al., 2010). The U.S. Energy Independence and Security Act of 2007 envisioned to increase renewable energy efficiency and availability (Sissine, 2007). The law requires 16 billion gallons of cellulosic biofuels in 2022. As a result, the expanded RFS2 program implicitly created a biofuel market, stimulated growth and reduced the risks of biofuel facility investments (Schnepf and Yacobucci, 2010) because fuel blenders are obliged to blend petroleum with biofuels. However, at present the utilization of woody biomass is sluggish because of the expensive cost of feedstock procurement (He et al., 2014) and the difficulty of processing biomass with high lignin content (Lane, 2015) relative to corn-based biofuels (Pimentel and Patzek, 2005). Further, low prices of wood chips and grindings, and harvest restrictions in some parts of the U.S. due to environmental concerns have limited the collection of woody biomass (Dirkswager et al., 2011). Galik et al (2009) noted however that biomass prices adjust as markets developed and harvesting technologies improved. For instance, attaching a small chipper to harvesting equipment increases production of wood chips (Greene et al., 2007).

Good timber management increases forestland owner income (Jacobson, 2008). Trees grow and increase in size and timber value (Langholtz et al., 2016; Coordes, 2016). Forest dynamics impacts tree growth, regeneration, and harvesting, and tree longevity affects forest stands (Pretzsch, 2009) as volume of biomass accrue after establishment. It also affects soil

quality, environmental conditions, tree species and stand density and forestry practices (Roth, 1989; Yang et al., 2006). Bergeron and Harvey (1997) state that forest dynamics are essential in biodiversity preservation and long-term productivity as evidenced in sequential rotations of different tree species. Understanding site conditions and climatic issues affecting growth is also important to effective forest management (Yang et al., 2006).

Stand growth, tree species, site productivity, rotation length, and regeneration are important factors to silvicultural planning. Fertilization increases growth rate and yield (Stovall et al., 2011). Fertilizer application can also guarantee timber regeneration and growth, enhance wildlife habitat, maintain aesthetic values and reduce management costs (Hopper & Applegate, 1995). Forest age is another essential issue that influences tree size, and soil thickness stimulates growth (Yang et al., 2006). As tree diameter increases, value shifts from pulpwood to sawtimber (Jacobson, 2008). Even-aged[3] stands could increase by 3-4 inches in diameter per decade (Jacobson, 2008).

Timber harvesting is integral to forest management, and if properly managed, improves growth and long-term timber value (Jacobson, 2008). Clearcut and thinning harvesting significantly impacts new and residual class stand structure (USDA-FS, 2016). It changes the landscape of the timberlands depending on the methods used. Clearcut creates an even-aged structure. This method is the simplest form of forest management but could have sizable site disturbance. Nevertheless, uneven-aged forest stands are more attractive to many owners because it leaves a continuous stand cover (USDA-FS, 2016; Pukkala et al., 2014) and results to better aesthetic forest value. Tahvonen (2016) found that “continuous cover management is optimal if the discounted revenues from thinning is higher than the interest of revenue in clearcut

[3] Forest that have trees of same species and age (Conrad, 1999)

harvesting and bare land value". Current silvicultural practices promote rotations of uniform growth and regeneration (Bergeron and Harvey, 1997).

Altering forest management practices changes forest stand composition (Washington Department of Natural Resources, 2016). Thinning[4] is a silvicultural practice that improves timber growth, yield, and maximizes revenue. For instance, an acre of planted southern pine could yield 10 cords after a commercial thinning harvest (McNeel, 2016). It minimizes competition for sunlight, soil nutrients, and removes undesirable trees (Virginia Department of Forestry, 2016). However, effective thinning must be conducted before tree canopies affect growth.

There are several options available for forest regeneration. These options are part of the harvesting plan to maintain timber values and reduce regeneration costs (Jones, 1991). Regeneration could be either natural or artificial. Natural regeneration involves transition of stand types after clearcut of which stands regenerate from seeds, stump sprouts or root suckers (Bergeron and Harvey, 1997) to trees formerly occupying the land (Virginia Department of Forestry, 2016). Most often, hardwood and other shade intolerant species regenerate after a clearcut harvest (Jones, 1991). As a result, artificial regeneration is prevalent among intensively managed timberlands. It includes direct seeding or planting seedlings in timberlands where seedlings of valued species are lacking (Jones, 1991). It is also appropriate in "afforestation and rehabilitation of preferred species in forest sites" (Virginia Department of Forestry, 2016).

The objective of the study is to provide estimates of the changes of South region timberlands over time and its ability to meet conventional timber products demand and biomass for bioenergy. In this study, ForSEAM was modified to track changes in growth, available acres

[4] Thinning refers to the harvesting/removal of trees without subsequent regeneration that generates substantial net revenue, and shapes the future value development of the remaining forest stand (Coordes, 2016)

for harvest and stand regeneration over time. Results of the study can assist decision and policy makers, forestland owners and foresters interested in cellulosic bioenergy.

Forest stand structure affects tree growth, and changes in biomass growth are manifested in stem size (Sievänen et al., 2000). Hahn and Hansen (1991) described that estimating the volume of standing trees is basic to any forest inventory. Forest Inventory Analysis requires models to estimate future growth and volume (Pienaar and Harrison, 1988). Hahn and Hansen (1991) and Hansen (2002) explained that there are available set of models that consistently estimate volume in most timber species in the U.S. Factors such as stand growth and mortality (Weiskittel et al., 2011), tree species and age, diameter and merchantable height (Hahn, 1984), and productivity index are important in estimating biomass volume (Hahn, and Hansen, 1991). These estimates are useful in planning and scheduling timber harvest as well as removing trees during thinning operation (Bowers et al., 2002).

Several studies related to optimizing the harvest of conventional timber and biomass have been conducted. Supply curves of conventional timber products and woody biomass usually are solved using optimization models. These models solve large and complex problems involving numerous decision variables. For instance, He et al (2014) and Langholtz et al (2016) developed a LP model to calculate the optimal harvesting costs of conventional timber and woody biomass feedstock supply for bioenergy across conterminous U.S. Their findings suggest that harvesting forest residues and non-merchantable timber could contribute to the overall targeted demand on cellulosic bioenergy feedstock. At lower market prices, logging residues can be a major potential source of supply biomass. Silva et al (2016) developed LP to generate timber production routes to minimize cost of harvesting and forest road maintenance. Kucuker and Baskent (2015) also examined the effects of monetary values on timber management strategies of minimum

harvesting ages. They reported that harvesting depends largely on initial forest's age class structure. Most of the studies explored on estimating optimal supply of woody biomass available using LP; however, few have tracked the changes of tree growth and timberland acres harvested over a continuous period.

Methods

In the study of Avila (2017), timberland acres harvested and regenerated were assumed fixed throughout the modeling period. In this study, ForSEAM was modified and improved to track the annual changes on existing acreage of timberlands harvested and regenerated as well as the acres remaining that would be available for harvest over time within the ½-mile road harvest distance used in the billion-ton 2016 analysis. The decision to use the ½-mile road harvest distance was based on the premise that about 97% of the timberlands in the South are located within this distance, thus assumed that more biomass is also available.

Two scenarios are examined. Scenario 1 assumed that existing stand growth and acreages were modeled as they were in the billion-ton 2016 analysis and Scenario 2 tracked the changes in stand growth and regeneration, and acres harvested throughout the modeling period. While similar methods of calculation and parameter estimates were applied from the study of Avila (2017), there were considerable modifications of features in the model. These modifications allowed the model to track changes in growth and acreages over time, thus increasing the precision of biomass supply estimates over time. First, the ForSEAM transition matrix was updated using the estimated FIA individual state level tree data. This transition matrix contains tree types, class stands, and stand age for tree species to move from small diameter class diameter (class 3) to larger size diameter class such as class 2 (pulpwood) or class 1 (sawtimber). The data were placed into Agricultural Statistic Districts (ASDs). The stand age is an important

decision variable as it indicates periods where a tree could grow and increase diameter, size and form over time. The right-hand side (RHS) of the growth constraint (net growth) was modified using the updated transition matrix to trace annual changes of stand growth and timberland acreages after each harvest.

These changes resulted in a significant increase in computer run time and memory requirements. To examine the impact of these changes, the study area was limited to the Southern U.S. (South) region. The southern region was selected because the South is a major producer of timber with 42% of U.S. timberlands are located in the South. The South has the potential to supply about 50% of biofuels demand in the U.S. In addition, to the changes above, the analysis excluded acreages without yield information. Furthermore, all sustainability assumptions in the model described in the study of Avila (2017) are maintained.

As described above, the model was modified to track the dynamics of stand growth, regeneration and timberland acreages available for harvest to meet conventional timber demand and woody biomass for bioenergy. Initially, existing acres available for harvest were calculated. These acres were classified further into: a) existing available acres but class stands do not change and, b) existing acres with class stands that vary over the modeling period (Figure 9). The model calculated how many existing acres were harvested and regenerated and those acres that were not available for harvest until regenerated. The following equations were used in tracking the changes of stand growth and existing acres available for harvest.

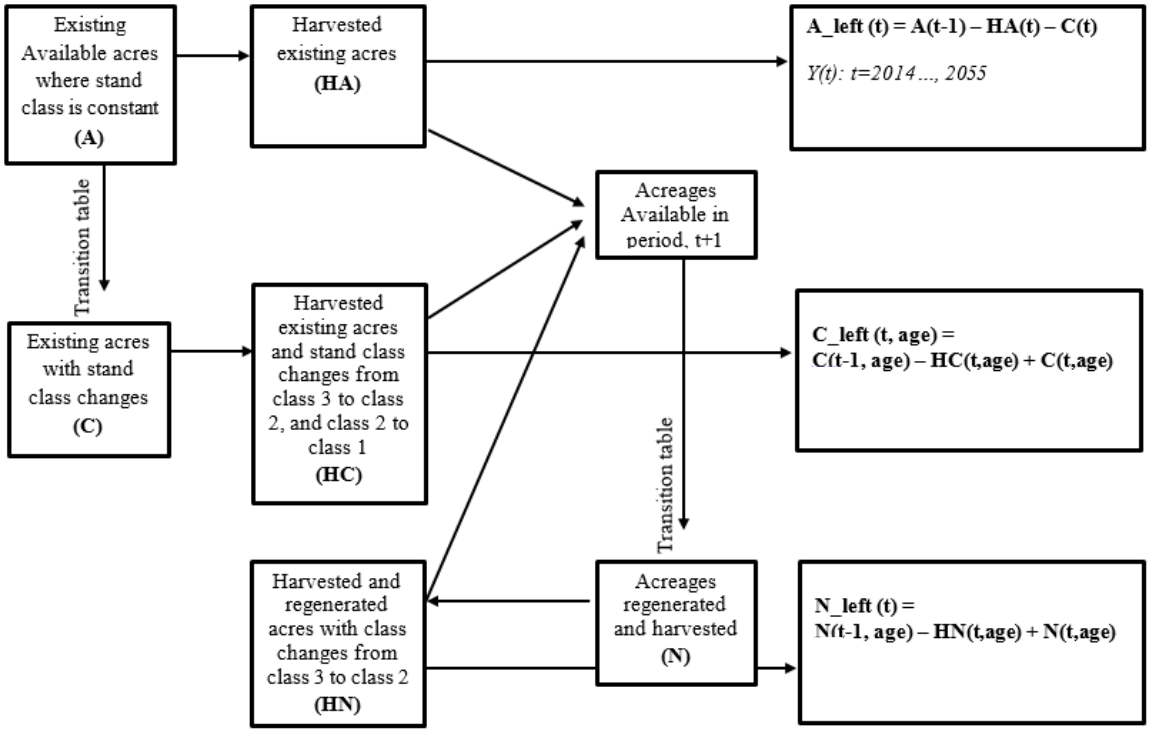


Figure 9. Modified ForSEAM flowchart to track changes of acreage harvested and regenerated, 2020-2055

a. Existing available acres left and stand class do not vary in period, t

$$\mathbf{A_left}_t = A_{t-1} - HA_t - C_t \quad (1)$$

where:

A_left_t acres remaining after harvest in current period, t;

A_{t-1} existing acres in the previous period, t-1;

HA_t acres harvested in the current period, t;

C_t existing acres that vary at current period, t;

b. Existing acres available left and stand class vary (C)in period t and age

$$\mathbf{C_left}_{t,age} = C_{t-1,age} - HC_{t,age} + C_{t,age} \quad (2)$$

where:

$C_left_{t,age}$ acres remaining after harvest in current period, t and stand age;

$C_{t-1,age}$ existing acres in the previous period, t-1 and stand age;

$HC_{t,age}$ harvested acres in the current period, t and stand age;

$C_{t,age}$ existing acres that vary at current period, t and stand age;

c. Harvested and regenerated acres and class vary from class 3 to class 2

$$\mathbf{N_left}_t = N_{t-1,age} - HN_{t,age} + N_{t,age} \quad (3)$$

where:

$N_left_{t,age}$ acres remaining after harvest in current period, t and stand age;

$N_{t-1,age}$ existing acres in the previous period, t-1 and stand age;

$HC_{t,age}$ harvested acres in the current period, t and stand age;

$N_{t,age}$ regenerated acres vary in period t and stand age;

The updated transition matrix was embedded in ForSEAM to simulate changes of the existing available class stands for harvesting in the succeeding period. Other remaining class stands not harvested during the current period are expected to grow and move from class 3 to class 2 and class 2 to class 1 stands and so on. The model iterated the annual stand net growth over the modeling period based on the acreages and the incremental diameter changes in stand class with DBH 5> inches (i.e. class 1 and class 2 stands) that maybe available for harvest. Class 3 stand acres were assumed to regenerate during the modeling period. This new ForSEAM transition matrix contains records on class stands, tree species and stand age where class stand move from small diameter class to a larger diameter in all ASDs, i =1…305, stand type $j = 1 \ldots 5$, stand class k = 1…3, slope m = 1…2, ownership o=1…2 and time period, t (year 2020-2055). After harvest of class 1 stand and even class 2 stand (pulpwood), forest acreages were assumed

to regenerate back to class 3 in all ASDs *i*, stand type *j*, class *k*, slope *m*, ownership *o*=1…2 and wood type, *p*=1…2. Those acreages that do not enter into the solution were assumed to have a Diameter at Breast Height less than 5 inches (DBH < 5”) and allowed to grow until they become class 2 or class 1. The simulation continued until 2055. Thus, if acres of timberland were harvested in the current period, these acreages are no longer available for harvest in the next period. Moreover, the model specified that only class 2 stands were thinned. A thinning and clearcut harvest proportion is found in the report of Langholtz et al (2016). South has about 28% clearcut portion of which thinning yield is 70% of the total clearcut yield. This indicates that in one acre of land, thinning removed about 70% of pulpwood size (Class 2) trees. After thinning, remaining stands were set aside and not available for harvest until they grow in size and become class 1 (sawtimber). As common practice in forest management, thinning promotes forest health, faster tree growth and increases value because due to larger diameter of the remaining stand. Thinned timbers can be used as feedstock for bioenergy, chips, landscaping and other marketable products. Meantime, no thinning was done on class 3 stands.

Shadow prices were developed for the demand scenario on biomass production target goals. Woody biomass target is varied from 5 million dry tons to 120 million dry tons at 5-million dry ton increment to simulate the shadow values and to plot woody biomass supply curves overtime. These shadow prices and the associated acres for the scenario demands (dry tons of biomass) were reported as logging residues or whole-tree biomass across selected years.

ForSEAM Model

ForSEAM is a linear cost optimization model (Langholtz et al., 2016). The objective of the model was to minimize the total costs (harvest costs and stumpage cost) to meet conventional demand (*X)*, whole trees for biomass (*Z*) and logging residue collection (*U*) using cut-to-length

or thinning cutting options subject to the land availability and harvesting intensity, timber growth, inter-period determination, conventional wood demand and woody biomass supply targets.

$$minimize\ COST = \sum_{i=1}^{305}\sum_{j=1}^{5}\sum_{k=1}^{2}\sum_{m=1}^{2}\sum_{c=1}^{2}\Big[\sum_{o=1}^{2}[X_{i,j,k,o,m,c,p,t}\alpha_{i,j,k,c,t}(CL_{i,j,o,m,c} + SC_{i,j,k}) + XCTL_{i,j,k,o=1,m,c,p,t}\alpha_{i,j,k,c,t}(CTL_{i,j,m,c} + SC_{i,j,k})\ \Big] + \sum_{i=1}^{305}\sum_{j=1}^{5}\sum_{k=2}^{3}\sum_{m=1}^{2}\sum_{c=1}^{2}\sum_{o=1}^{2}[Z_{i,j,k,o,m,c,t}\beta_{i,j,k,c,t}(CW_{i,j,o,m,c} + SC_{i,j,k}) + \sum_{i=1}^{305}\sum_{j=1}^{5}\sum_{k=1}^{2}\sum_{m=1}^{2}\sum_{c=1}^{2}\sum_{o=1}^{2}[U_{i,j,k,o,m,c,t}\theta_{i,j,k,c,t}(CR_{i,j,m,c} + SCR_{i,j,k}) \quad (4)$$

c = Harvesting options, c=1 thinning (partial cut) and c=2 clearcut

i = Agricultural Statistics District (ASD) 1,…,305

j = stand type *j*=1 upland hardwood *j*=2 lowland hardwood *j*=3 natural softwood, *j*=4 planted softwood, and *j*=5 mixed wood

k = stand diameter class, *k=1* has a diameter >11 inches for hardwood and >9 inches for softwood, k = 2 has diameter range ≥5 inches but <11 inches for hardwood and ≥5 inches but <9 inches for softwood, and k = 3 has diameter <5 inches for all stand types

m = Slope of the land, *m* = 1 slope is ≤40% and *m*=2 has a slope of ≥40%

o = Ownership of the forestland, *o*=1 private and *o*=2 federal

p = Conventional timber product type, p=1 sawtimber and p=2 pulpwood t = time period

Where:

$X_{i,j,k,m,c,p,t}$ acreage decision variables of timberland full tree harvested to meet conventional demand in ASD *i*, by stand type *j*; by stand diameter class *k*; by conventional timber product type *p*; by Ownership *o*;

$\alpha_{i,j,k,c,t}$ 2015 log yield in ASDs *i*, stand type *j*, stand diameter class *k*, cutting options *c*, conventional timber product type *p* at time *t*;

$CL_{i,j,m,c}$ log harvesting costs for partial cut and clear trees (*$ per dry ton*) in ASD *i* for tree species *j*, land slope *m*, and cutting option *c* (*$ per acre*);

$SC_{i,j,k}$ log stumpage costs (*$ per dry ton*) in ASD *i* for tree species *j*, and stand diameter class *k* (*$ per acre*);

$XCTL_{i,j,k,m,c}$ acres of timberland that were harvested using cut-to-length logging option in ASD i for tree species j, stand diameter class k, land slope m, and cutting option c and conventional wood product p at time period t and only private timberland harvested using cut-to-length method;

$CTL_{i,j,m,c}$ logging harvest costs for cut-to-length (CTL) (*$ per dry ton*) in ASD i for tree species j, land slope m, and cutting option c (*$ per acre*);

$Z_{i,j,k,m,c,t}$ acres of timberland classified as class 2 and class 3 whole trees harvested to meet woody biomass demand for all $i, j, m, t, c, k = 2,3$;

$\beta_{i,j,k,c,t}$ whole tree yield in ASD i for tree species j, stand diameter class k, cutting option c, and time t;

$CW_{i,j,m,c}$ whole tree harvesting costs for partial cut and cleared trees in ASD i for tree species j, land slope m, and cutting option c (*$ per acre*);

$U_{i,j,k,m,c,t}$ acres of logging residue harvested to meet woody biomass demand for all i, j, k, m, c, t;

$\theta_{i,j,k,c,t}$ logging residue yield in ASD i for tree species j, stand diameter class k, cutting option c and time t;

$CR_{i,j,m,c}$ logging residue harvesting costs for partial cut trees and clear-cut trees in ASD i for tree species j, land slope m, and cutting option c;

$SCR_{i,j,k}$ Stumpage costs of logging residues in ASD i for tree species j, and stand diameter class k.

ForSEAM solutions were solved in two steps. At initial period, t_1, the model ran without incorporating growth and woody biomass supply targets constraints into the model structure. This provides a benchmark on the estimated renewable biomass supply. The optimal solutions to X^* and $XCTL^*$ were used to change the right hand side (RHS) of growth constraints (equation 5). Next, the model solved the objective function and all the constraints. RHS of woody biomass supply target varied from 5 million dry tons to 120 million dry tons at 5-million dry ton increments to simulate the shadow values (λ). These shadow values were used to plot the supply curve of woody biomass.

State Growth constraint Equation (5) was a key constraint that ensures harvest of conventional timber, whole-tree biomass and logging residues should not exceed the total standing wood available for harvest (total growth), $\bar{G}_{i,j,k,m}$ in (*cubic feet*) for all $i, j, k, and\ m$ and annual growth $g_{i,j,k,m}$ in the state that ASD i is located for tree species j, stand diameter class k, land slope m.

$$\sum_{si}\sum_{c=1}^{2}\sum_{p=1}^{2}\left(X_{si,j,k,\mathrm{o},m,c,p,t} + XCTL_{si,j,k,\mathrm{o}=1m,c,p,t}\right)\alpha_{si,j,k,c,t} + \sum_{c=1}^{2} Z_{si,j,k,\mathrm{o},m,c,t}\beta_{si,j,k,c,t} + \sum_{c=1}^{2} U_{si,j,k,\mathrm{o},m,c,t}\theta_{si,j,k,c,t} \leq \sum_{si}\bar{G}_{si,j,k,\mathrm{o},m} + g_{si,j,k,m} \quad \forall \text{ all } si, j, \mathrm{o}, m, t, k \tag{5}$$

Results

Woody biomass supply curve

The potential supply of woody biomass within the ½-mile road harvest distance is analyzed in Figure 10. As can be seen in the figure, the supply of woody biomass is declining over time. This decline in biomass supply occurs because harvested land projected is removed and does not reenter until regeneration occurs. Yield productivity remains unchanged when it regenerates and must re-establish its original cover. The harvesting rate is limited to 5% per ASD in any given year. Tracking growth and existing acres allows the model to simulate the change in available woody biomass supply and acreage harvested over time. Prices greatly influenced woody biomass supply availability. As marginal price increases, biomass supply also increases (Table 8). For the period 2020 to 2055, changes in price from $52 per dry ton to $70 per dry ton, on average, increases the supply of biomass by more than 60% in both scenarios. However, scenario 2 generates higher biomass supply than scenario 1 except in 2055. Whole-tree, class 2 biomass (pulpwood size) provides most of the feedstock (Table 9). Thinning accounts roughly, 60% of the class 2 biomass harvested. Except in 2020, thinned biomass has a maximum supply

of about 39 million dry tons in scenario 1 at $68 per dry ton and 34 million dry tons in scenario 2 at $69 per dry ton (Tables 10 & 11). Throughout the modeling period, a potential 20 million dry tons of biomass supply from thinning could be available at prices ranging from $64 to $68 per dry ton. Over time, the biomass supply is declining and seemingly, class 2 stands disappear over the modeling period. Primarily, because after thinning, remaining acres could either be under regeneration and therefore not available for harvest or stands move to class 1. Consequently, this leads to reduced available class 2 lands and increase prices of thinned whole-tree biomass supply. Thus, an increase in feedstock demand for bioenergy increases collection of pulpwood size trees.

Being the major timber producer, the South can play a vital role in bioenergy development. The region supplies considerable volume of potential biomass and more available timberland acres for harvest than any other region in the US. In 2020, the potential supply of woody biomass was projected to total approximately 90 million dry tons at $70 per dry ton (Table 8). Nonetheless, at prices below $50 per dry ton, most available biomass consisted of logging residues. This is expected because the cost of collecting residues is lower than the cost of harvesting small diameter non-merchantable whole trees. Moreover, the supply of logging residues depends on the demand of conventional timber. As one would expect the supply of logging residues increases as the demand of conventional timber increases. In addition, the supply of whole tree woody biomass price responds to changes in price. As marginal prices increase, potential supply of woody biomass also goes up. Increasing the marginal price from $20 to $70 per dry ton increases the supply of biomass from non-merchantable timber by a factor of 3 and becomes an important source of woody biomass for bioenergy. In 2045, the potential available biomass in scenario 2 is 10 million dry tons higher than in scenario 1 when the price is

at $70 per dry ton. In 2055, biomass supply available is about 60 million dry tons with a marginal price of $80 per dry ton. Any additional increase in demand beyond 60 million dry tons will increase price sharply and the supply curves bend toward the left and may no longer be economically feasible to harvest as acres have less biomass available. As the harvesting horizon increases, available acres for harvest decline and both acres regenerated and not available for harvest have increased (Figure 11). As can be seen in the figure, acres remaining and available, and acreage regenerated and not available for harvest have changed over time. For the period 2020 to 2055, acres regenerated and not available for harvest have increased to 108 million acres (82%), roughly 2.55 million acres per year. Correspondingly, on the same period, the available acreages decline by about 54 million acres, and acres remaining drop to 34%. On average, acres harvested range from 3% to 4% of the total available timberland acres in any given year in the South.

Timberland acres and biomass harvested

The supply of woody biomass harvested at $70 per dry ton is analyzed in Table 9. There are two methods commonly used in biomass harvesting: clearcut and thinning. Clearcut is a key forest management because it minimizes costs, facilitates fast growth of saplings and promotes uniform stand regeneration. With this practice, tree species that do not favor canopy shading can grow and compete with enough sunlight exposure. This however, must adhere to the Best Management Practices to prevent soil erosion and protect water quality. From the period 2020 to 2055, scenario 2 has a higher potential supply of woody biomass than scenario 1 except in 2055. Hence, tracking stand growth and timberland acreages improves the ability of the model to estimate potential biomass supply through time. In 2020, about 90 million dry tons of potential supply of woody biomass are available. Approximately, 75% of biomass harvested is from class

2 whole-tree biomass. The logging residues supply did not vary much throughout the modeling period except in 2045. Most of the logging residues harvested are from class 1 (sawtimber) stands. This implies that most of the logging residues are collected together with the conventional timber products. Class 2 stands are virtually gone in 2045 because after harvest, it could either be regenerated and not available for harvest, and have not grown to pulpwood size or moved to class 1 (sawtimber). However, potential available biomass supply declines over time. For instance, in 2055 scenario 1 biomass supply declines by 1% which is equivalent to 70 million dry tons and 12.57 million dry tons or 86% in scenario 2, which results in a considerable reduction in supply of whole-tree biomass. This indicates that in 2055, most of the remaining stands in scenario 2 could be under regeneration and have less available acres for harvest. Across class stands, most of the woody biomass supply are harvested through the clearcut method. Thinning is applicable among class 2 whole-tree biomass. There is no thinning in class 3 stands and no clearcut harvesting of logging residues in class 2 stands (Table 9). However, clearcut harvest in class 3 stands provides biomass supply from the period 2020-2035. In 2040 through 2055, there are no longer available class 3 stands for harvest and instead allowed to regenerate and move to larger diameter size.

Changes in existing available acres, harvested and regenerated

Figure 11 presents the acreages available, harvested, remaining, and regenerated. Changes in acres available for harvest is tracked, namely: a) existing acres harvested with no changes in class stand, b) existing acres harvested and stand class changes from class 3 to class 2 and class 2 to class 1, and class stand regenerated and harvested until stand becomes class 2. Tracking changes of acres harvested and regenerated has important implications in the supply of conventional timber products and potential biomass for bioenergy. Of the 386 million timberland

acres in Conterminous U.S., about 42% (164 million acres) is located in the south (Table 11). Depending on prices, potential biomass available in the south range from 5 million dry tons to 90 million dry tons in 2020 and 60 million dry tons in 2055 (Figure 10). In 2020, the existing available acres for harvest is about 158 million acres. Of these acres, about 4% is harvested per period per ASD in any given year. Over time, on average, the available harvested acres declines about 3% per year. As can be seen on the figure, in 2020, majority of the acreages harvested are existing timberland acres with no changes in class (97%) implying that south have more acres of timberlands available for harvest in the current period, and decreases thereafter until 2055. In 2020 through 2055, available acres decline from 157.9 million to 103.8 million. On the same period, acres regenerated and acres not available for harvest increases from 25.9 million acres to 108.20 million acres. The quantity accounts both the acreages harvested in the last 5 years plus acreages that were thinned. Similarly, about 5.93 million acres are harvested in 2020 in existing stands (Table 10). Specifically, the harvested acres in every year decline from 5.93 million in 2020 to 2.8 million in 2055 (Figure 11). This shows that over time, acres harvested declines approximately 5% and 6% in scenario 2 and scenario 1, respectively. Increased pressure on the nation's forests results in a decreasing stock of available lands for harvest at $70 per dry ton. Harvesting class 3 lands results in a decrease in pulpwood (class 2) and hence the harvest costs increase as more class 1 (sawtimber) land is needed to meet both traditional and biomass demands. Over the modeling period, total available acres for harvest declines by 54% in scenario 2 and 64% in scenario 1. As available acres for harvest declines, acreage under regeneration and acres not available for harvest increase.

Discussion and Conclusion

Forest growth and development are vital to environmental sustainability, and to maintain ecological balance as it supports the watersheds, and diversity of flora and fauna species. Forests are a vast carbon sink, storing carbon as biomass. Forests serve as a frontier to minimize impacts of climate change. If properly managed, biomass can be harvested continuously to provide a stream of income and help protect the environment. However, its growth is highly influenced by location, plant density, sunlight, and productivity. Trees grow best in areas with better productivity index and sunlight exposure. Some trees are able to compete under the canopy while others need sufficient sunlight to grow robustly.

Woody biomass is a potential cellulosic feedstock for biofuel production. Its demand could potentially increase under the Energy Independence and Security Act of 2007. The law requires renewable fuel standards program to produce 16 billion gallons of cellulosic biofuels in 2022 and obligate parties to blend biofuels in transportation fuels. Forest logging residues and non-merchantable timber are potential feedstocks to meet some of the required demand and could generate economic opportunities to rural economies. This chapter presents woody biomass supply curve under varying marginal prices in period 2020 through 2055. ForSEAM, a linear programming model is used to estimate feedstock supply to meet demands subject to timberland availability and harvest intensity, proportion of clearcut and thinning, growth and inter-period class diameter determination, conventional timber demand and woody biomass targets. Improvements in the model include the updating of ForSEAM transition matrix to trace the annual changes of stand growth and timberland acreages after each harvest. The matrix contains data on tree types, class stands, and stand age as small diameter trees move to a larger diameter over time. The estimated FIA data on acres that have no yield information are excluded in the

simulation. Two scenarios within the ½-mile road harvest distance are examined: a) timberland stand growth and acreages are assumed constant, and b) stand growth and acreages vary over time. The model solves in two steps. Initially, both the timber growth and woody biomass supply target constraints are excluded in the model structure. This provides benchmark on the estimated renewables. Optimal solutions are used to vary the growth (net growth) constraints right hand side. Growth is varied to reflect changes in available acres harvested in the current period, acres under regeneration and acres available for harvest in the next period. Tracking on acreage available, remaining and regenerated improves the ability of the model to provide estimates on the changes in timberland acres between and after harvest. The model solves the objective function using set of constraints (Langholtz et al., 2016). Woody biomass targets vary from 5 million dry tons to 120 million dry tons at 5-million dry ton increment to simulate the shadow values and plot woody biomass supply curves over time. With an increased demand placed on U.S. forestlands, the forests become young and require time to regenerate and the mature forest area decreases. Findings of the study could assist the government in formulating policy actions toward sustainable timber harvesting and utilization of woody biomass feedstock by providing incentives on the use of improved tree genomics to increase productivity and hasten stand age maturity to allow more frequent timberland harvests. A policy action could also be directed on training specialists on biomass feedstock utilization and educating timberland owners on the importance of forest woody biomass in the development of bioenergy program.

There are some limitations in interpreting the results. The study area is confined in the southern region due to limited computer memory and computer run time. All estimates rely on the FIA data in which class 3 stands (trees with DBH < 5”) are not included in the inventory, but rather considered as seedlings/saplings. In addition, the transaction costs embedded in the model

cover only the costs at the roadside, and does not include transportation to the biorefinery or blending facilities. POLYSYS does not site facilities, the distance traveled is unknown, therefore cannot calculate the transportation cost.

Future directions should focus on relaxing constraints, to some extent, allow the model assume conversion of natural pine to managed plantations after harvest on privately owned lands. Additionally, ForSEAM may be modified to include calculation of potential stream of incomes and net present values from pre-commercial and commercial thinning. Most forestland owners do not practice thinning because revenues often cannot cover costs of harvesting, and the bioenergy market is limited. Likewise, integrate ForSEAM and BioFLAME models to site economically feasible biorefineries, calculate costs of transportation from the roadside to biorefineries and estimate transportation emission. Finally, expand the study to the entire US to estimate total potential supply of woody biomass. However, this requires fast computing machine with higher memory.

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Appendix

Table 8. Woody biomass by scenario, feedstock type and price in the South, 2020-2055

		Scenario 1: ½-mile road harvest distance, 2016 BTS[a]			Scenario 2: ½-mile road distance with stand growth & acreage tracking[5]		
Year	Marginal Cost	Logging residues	Whole-tree biomass	Total	Logging residues	Whole-tree biomass	Total
	($/dry ton)			(Million dry tons)			
2020	52	11.4	18.6	30.0	11.40	18.60	30.0
2020	62	11.4	38.6	50.0	11.39	38.61	50.0
2020	70	10.7	79.3	90.0	10.69	79.31	90.0
2025	52	12.1	12.9	25.0	12.17	12.83	25.0
2025	62	12.1	22.9	35.0	12.18	22.82	35.0
2025	70	11.5	48.5	60.0	11.55	53.45	65.0
2030	52	13.0	12.0	25.0	13.07	11.93	25.0
2030	62	13.0	22.0	35.0	13.08	16.92	30.0
2030	70	12.4	42.6	55.0	12.44	47.56	60.0
2035	52	13.7	1.3	15.0	13.70	1.30	15.0
2035	62	13.7	36.3	50.0	13.68	31.32	45.0
2035	70	13.0	67.0	80.0	12.94	62.06	75.0
2040	52	13.6	1.4	15.0	13.65	0.0	13.6
2040	62	13.6	26.4	40.0	13.65	26.35	40.0
2040	70	12.9	62.1	75.0	12.79	62.21	75.0
2045	52	0.0	1.5	1.5	13.57	1.43	15.0
2045	62	0.0	6.5	6.5	13.55	16.45	30.0
2045	70	0.0	42.1	42.1	12.72	52.28	65.0
2050	52	13.3	6.7	20.0	0.0	0.0	0.0
2050	62	13.3	11.7	25.0	13.54	1.46	15.0
2050	70	12.7	42.3	55.0	12.71	42.29	55.0
2055	52	13.3	11.7	25.0	13.34	1.66	15.0
2055	62	13.3	26.7	40.0	13.33	6.67	20.0
2055	70	12.6	57.4	70.0	12.57	42.43	55.0

[a]2016 *Billion-Ton Study*: acres harvested are assumed constant throughout the modeling period

[5] Forest tree stand growth, regenerated, acreage harvested and remaining acres are tracked every period

Table 9. Woody biomass supply in timberland in the South by scenario, year, feedstock type and stand type at $70 per dry ton, 2020-2055

	Scenario 1: ½-mile road harvest distance, 2016 BTS									Scenario 2: ½-mile road harvest distance with stand growth & acreage tracking								
	Logging Residues			Whole-Tree biomass						Logging Residues			Whole-Tree biomass					
	Class 1 Stand	Class 2 Stand		Class 2 Stand		Class 3 stand		Total		Class 1 Stand	Class 2 Stand		Class 2 Stand		Class 3 stand		Total	
Year	CC[b]	CC	T[c]	CC	T	CC	T	CC	T	CC	CC	T	CC	T	CC	T	CC	T
	(million dry tons)									(million dry tons)								
2020	10.4	0.0	0.3	26.1	41.5	11.7	0.0	48.2	41.8	10.4	0.0	0.2	26.3	41.3	11.7	0.0	48.4	41.6
2025	11.3	0.0	0.2	14.6	24.4	9.5	0.0	35.5	24.5	11.1	0.0	0.4	18.1	25.9	9.5	0.0	38.7	26.3
2030	12.2	0.0	0.2	12.9	21.4	8.3	0.0	33.4	21.6	11.8	0.0	0.6	17.7	21.6	8.3	0.0	37.8	22.2
2035	12.7	0.0	0.0	25.2	41.4	0.5	0.0	38.4	41.4	12.4	0.0	0.5	29.1	32.5	0.5	0.0	42.0	33.0
2040	12.5	0.0	0.4	23.7	38.4	0.0	0.0	36.2	38.8	12.5	0.0	0.4	23.7	38.4	0.0	0.0	36.2	38.8
2045	0.0	0.0	0.0	17.0	25.1	0.0	0.0	17.0	25.1	0.0	0.0	0.0	17.0	25.1	0.0	0.0	17.0	25.1
2050	12.4	0.0	0.3	15.9	26.4	0.0	0.0	28.3	26.7	12.0	0.0	0.8	22.0	20.3	0.0	0.0	33.9	21.1
2055	11.9	0.0	0.7	22.3	35.1	0.0	0.0	34.2	35.8	11.7	0.0	0.9	0.0	0.0	0.0	0.0	11.7	0.9

[b]CC = Clearcut; [c]T=Thinning

Table 10. Scenario 1: Thinned woody biomass potential supply in the South by year and price

Total Biomass Demand	Year							
	2020		2030		2040		2050	
	Thinned Biomass		Thinned Biomass		Thinned Biomass		Thinned Biomass	
Million dry tons	Million dry tons	$/dry ton	Million dry tons	$/dry ton	Million dry tons	$/dry ton	Million dry tons	$/dry ton
20	4	40.28	3	40.35	4	54.37	4	51.75
25	4	51.29	3	54.07	7	54.64	4	62.55
30	5	51.51	5	54.68	10	54.71	5	63.78
35	6	53.30	5	63.75	13	54.78	9	64.02
40	6	54.04	9	66.33	16	62.16	14	64.27
45	9	54.67	13	67.97	16	62.41	18	65.50
50	10	62.26	17	68.29	17	62.77	22	66.18
55	11	63.50	22	69.32	22	63.96	27	66.58
60	16	63.76	0	0.00	26	66.14	0	0.00
65	20	63.87	0	0.00	30	68.25	0	0.00
70	25	64.12	0	0.00	35	68.34	0	0.00
75	29	66.25	0	0.00	39	68.53	0	0.00
80	33	68.06	0	0.00	0	0.00	0	0.00
85	37	68.28	0	0.00	0	0.00	0	0.00
90	42	68.89	0	0.00	0	0.00	0	0.00

Table 11. Scenario 2: Thinned woody biomass supply in the South by year and price

Total Biomass Demand	Year							
	2020		**2030**		**2040**		**2050**	
	Thinned Biomass		Thinned Biomass		Thinned Biomass		Thinned Biomass	
Million dry tons	Million dry tons	$/dry ton	Million dry tons	$/dry ton	Million dry tons	$/dry ton	Million dry tons	$/dry ton
20	4	40.28	3	40.35	4	53.16	4	62.41
25	4	51.25	3	54.09	4	53.64	4	62.52
30	5	51.47	5	62.07	6	54.34	4	63.10
35	6	53.30	5	62.43	9	54.42	6	64.30
40	6	54.06	6	63.84	10	62.37	9	65.69
45	9	54.63	10	66.16	10	62.49	13	66.39
50	10	62.32	14	66.68	12	63.93	17	67.48
55	11	63.50	18	67.78	17	64.92	21	68.30
60	16	63.77	22	68.33	21	67.85	0	0.00
65	20	63.87	0	0.00	25	68.21	0	0.00
70	24	64.13	0	0.00	30	68.36	0	0.00
75	29	66.97	0	0.00	34	69.10	0	0.00
80	33	68.06	0	0.00	0	0.00	0	0.00
85	37	68.29	0	0.00	0	0.00	0	0.00
90	42	68.99	0	0.00	0	0.00	0	0.00

Table 12. Timberland acres harvested in the South by year, feedstock, and stand class at $70 per dry ton, 2020-2055

		Scenario 2: ½-mile road harvest distance with stand growth and acreage tracking[6]								
		Logging Residues			Whole-Tree biomass					
		Class 1 Stand	Class 2 Stand		Class 2 Stand		Class 3 stand		Total	
Scenario	Year	CC[b]	CC	T[c]	CC	T	CC	T	CC	T
					(million acres)					
Existing Stand with no changes in Class	2020	1.51	0.00	0.07	0.72	1.62	1.85	0.00	4.08	1.68
	2025	1.19	0.00	0.10	0.41	0.53	1.29	0.00	2.89	0.64
	2030	1.17	0.00	0.10	0.32	0.28	0.96	0.00	2.44	0.38
	2035	1.21	0.00	0.03	0.47	0.03	0.06	0.00	1.74	0.06
	2040	1.14	0.00	0.00	0.36	0.01	0.00	0.00	1.50	0.01
	2045	1.02	0.00	0.00	0.14	0.01	0.00	0.00	1.16	0.01
	2050	0.91	0.00	0.00	0.00	0.00	0.00	0.00	0.91	0.00
	2055	0.81	0.00	0.00	0.00	0.00	0.00	0.00	0.81	0.00
Existing Stand and class stand changes from class 3 to class 2 and class 2 to class 1	2020	0.00	0.00	0.00	0.00	0.17	0.00	0.00	0.00	0.17
	2025	0.35	0.00	0.00	0.06	0.58	0.00	0.00	0.41	0.58
	2030	0.37	0.00	0.06	0.11	0.41	0.01	0.00	0.49	0.47
	2035	0.32	0.00	0.12	0.18	1.08	0.00	0.00	0.50	1.20
	2040	0.32	0.00	0.07	0.20	0.87	0.00	0.00	0.52	0.94
	2045	0.34	0.00	0.09	0.27	0.54	0.01	0.00	0.63	0.63
	2050	0.34	0.00	0.13	0.26	0.12	0.00	0.00	0.61	0.25
	2055	0.35	0.00	0.09	0.21	0.04	0.00	0.00	0.56	0.14
Stand regenerated and harvested until it becomes class 2	2020	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	2025	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	2030	0.00	0.00	0.00	0.00	0.25	0.00	0.00	0.00	0.25
	2035	0.00	0.00	0.00	0.00	0.41	0.00	0.00	0.00	0.41
	2040	0.00	0.00	0.00	0.05	0.61	0.00	0.00	0.05	0.61
	2045	0.00	0.00	0.01	0.11	0.69	0.00	0.00	0.11	0.70
	2050	0.00	0.00	0.04	0.18	0.85	0.00	0.00	0.18	0.89
	2055	0.00	0.00	0.11	0.23	0.89	0.00	0.00	0.24	1.01

[b]CC=clearcut; [c]T=Thinning

[6] Forest tree stand growth, regenerated, acreage harvested, acres remaining are tracked every period

Table 12. Continued

Scenario	Year	Logging Residues			Whole-Tree biomass				Total		Logging Residues			Whole-Tree biomass				Total	
		Class 1 Stand	Class 2 Stand		Class 2 Stand		Class 3 stand				Class 1 Stand	Class 2 Stand		Class 2 Stand		Class 3 stand			
		CC[b]	CC	T[c]	CC	T	CC	T	CC	T	CC	CC	T	CC	T	CC	T	CC	T
		Scenario 1: ½-mile road distance, 2016 BTS[a]									Scenario 2: ½-mile road distance with growth tracking								
		(million acres)									(million acres)								
All Stand **TOTAL**	2020	1.5	0.0	0.1	0.7	1.7	1.9	0.0	4.1	1.8	1.5	0.0	0.1	0.7	1.8	1.9	0.0	4.1	1.8
	2025	1.5	0.0	0.0	0.4	0.9	1.3	0.0	3.2	1.0	1.5	0.0	0.1	0.5	1.1	1.3	0.0	3.3	1.2
	2030	1.5	0.0	0.0	0.3	0.7	1.0	0.0	2.8	0.8	1.5	0.0	0.2	0.4	0.9	1.0	0.0	2.9	1.1
	2035	1.5	0.0	0.0	0.5	1.3	0.1	0.0	2.1	1.3	1.5	0.0	0.1	0.6	1.5	0.1	0.0	2.2	1.7
	2040	1.4	0.0	0.1	0.4	1.1	0.0	0.0	1.9	1.1	1.5	0.0	0.1	0.6	1.5	0.0	0.0	2.1	1.6
	2045	1.3	0.0	0.1	0.3	0.6	0.0	0.0	1.6	0.7	1.4	0.0	0.1	0.5	1.2	0.0	0.0	1.9	1.3
	2050	1.3	0.0	0.0	0.2	0.5	0.0	0.0	1.5	0.6	1.3	0.0	0.2	0.4	1.0	0.0	0.0	1.7	1.1
	2055	1.2	0.0	0.1	0.3	0.6	0.0	0.0	1.4	0.7	1.2	0.0	0.2	0.4	0.9	0.0	0.0	1.6	1.1

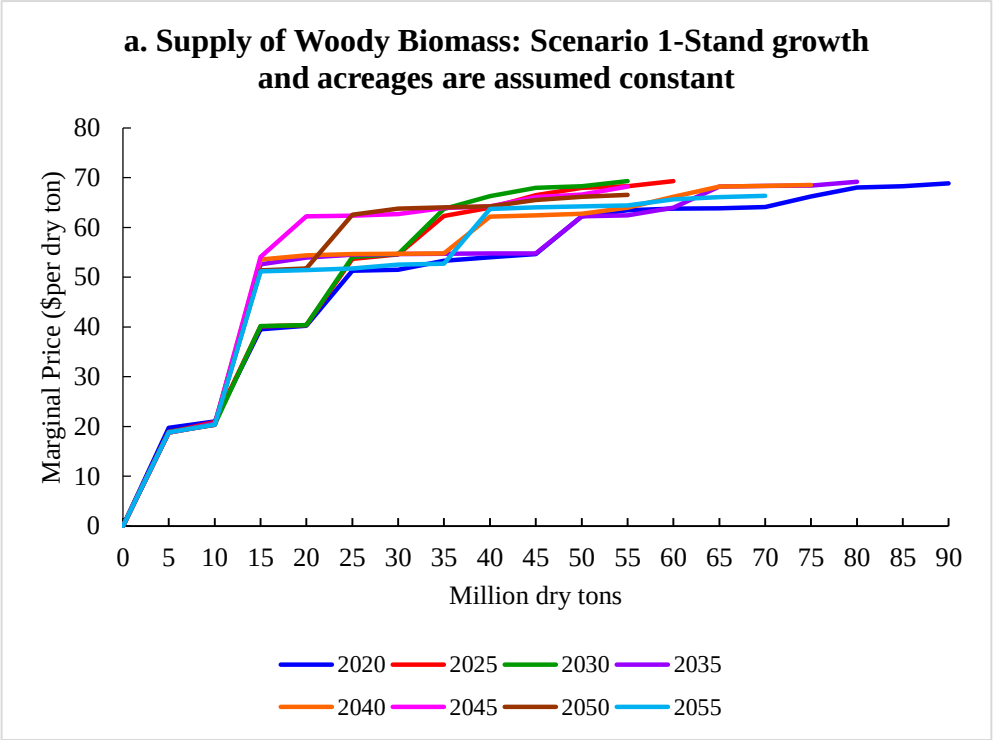
[a]*Billion-Ton Study*: acres harvested are assumed constant throughout the modeling period; [b]CC-Clearcut; [c]T-Thinning

Table 13. Timberland acres in the South included in the model by class, slope, ownership and stand type

	Class	Slope	Ownership	LHW	UHW	NP	PP	Mixed	Total
				Million acres					
South[7]	1	LE40	Private	12.4	27.9	13.3	12.0	7.4	73.1
			Public	1.8	3.5	4.2	0.8	1.3	11.6
		GT40	Private	0.7	5.4	0.2	0.0	0.3	6.6
			Public	0.0	1.2	0.1	0.0	0.1	1.5
	2	LE40	Private	4.6	11.6	5.3	13.8	3.8	39.0
			Public	0.4	1.1	0.7	0.8	0.4	3.5
		GT40	Private	0.0	1.1	0.1	0.1	0.1	1.4
			Public	0.0	0.2	0.0	0.0	0.0	0.2
	3	LE40	Private	3.6	10.0	2.5	4.7	3.6	24.3
			Public	0.3	0.7	0.4	0.2	0.3	1.9
		GT40	Private	0.0	0.4	0.0	0.0	0.0	0.5
			Public	0.0	0.1	0.0	0.0	0.0	0.1

LE40 - slope is less than 40; GT40 - slope is greater than 40

[7] FIA estimates timberland acres that do not have yield record are excluded from the analysis



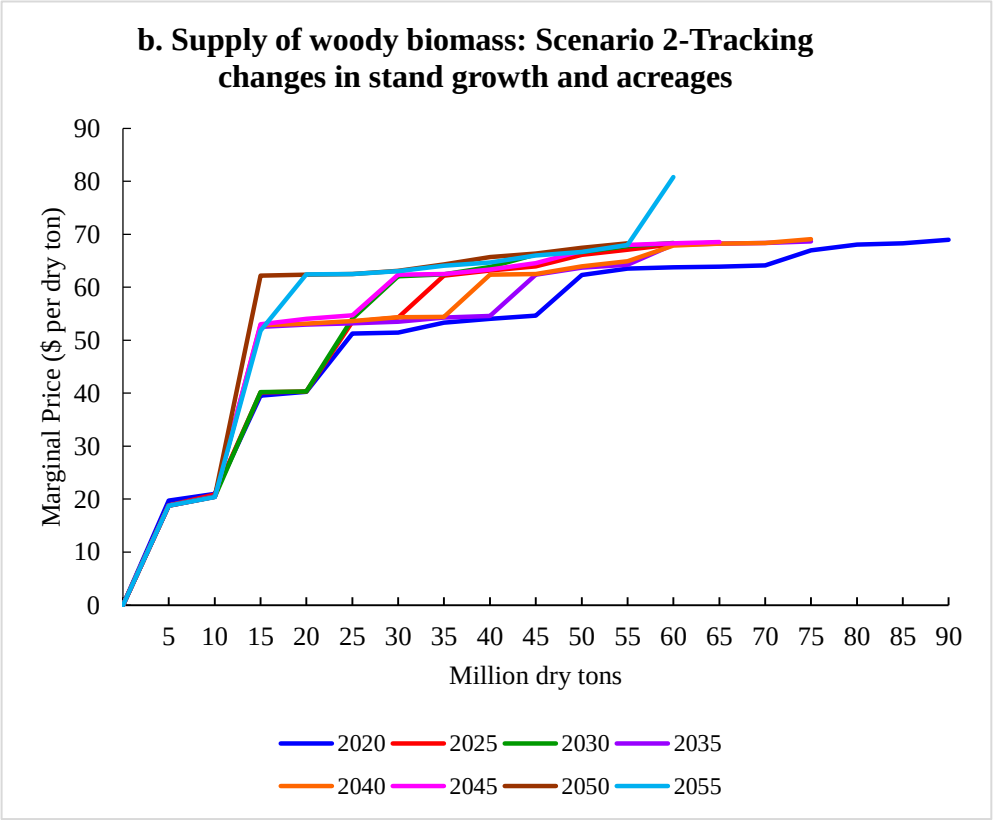
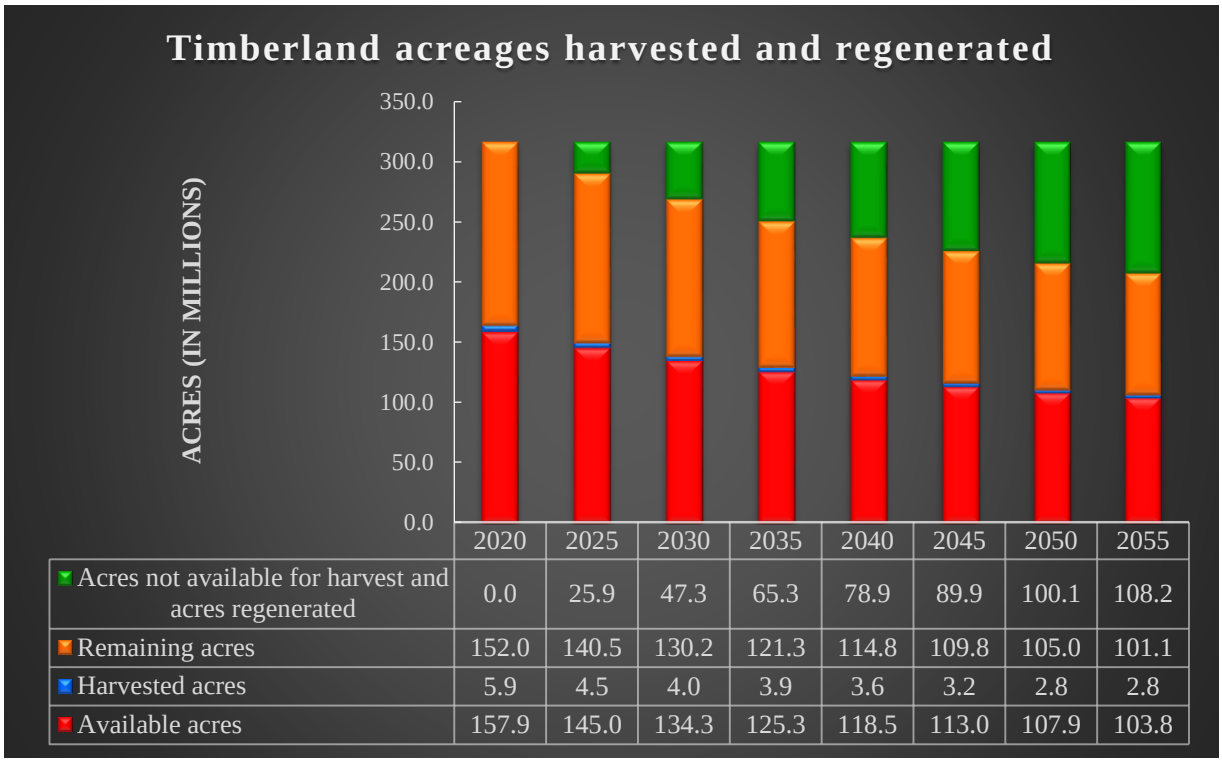


Figure 10. Woody biomass supply curve in the South, 2020-2055



	2020	2025	2030	2035	2040	2045	2050	2055
Acres not available for harvest and acres regenerated	0.0	25.9	47.3	65.3	78.9	89.9	100.1	108.2
Remaining acres	152.0	140.5	130.2	121.3	114.8	109.8	105.0	101.1
Harvested acres	5.9	4.5	4.0	3.9	3.6	3.2	2.8	2.8
Available acres	157.9	145.0	134.3	125.3	118.5	113.0	107.9	103.8

Figure 11. Changes in timberland acres harvested and regenerated in the South, 2020-2055

Chapter IV: Assessment on the Potential Supply of Forest Biomass to Prospective Biofuel Refineries in the Southeast Region of the United States

Abstract

The expanded Renewable Fuel Standards program of the Energy Independence and Security Act of 2007 sets the desired level of additional cellulosic biofuels to be used in the nation's fuel supply. The collection of logging residues and the utilization of mill wastes increases the feedstock supply. These woody biomass sources exist and are abundant. However, concerns over costs of harvesting and transportation must be competitive with other established feedstock on the market. The southeast region is a major producer of timber, thus logging residues and mill wastes are substantial feedstock sources that can supplement the supply of ethanol from corn- and sugarcane-derived biofuels. This study focuses on the use of logging residues and mill waste for bioenergy. It examines the optimal site for biorefineries and the associated feedstock costs. This study also evaluates the potential economic impact of biofuel production in the southeast region. Two models are used in this study; BioFLAME, a GIS-based transportation cost minimization model designed to simulate ideal site of biorefinery facilities and provide estimates on the lowest cost of feedstock, and IMPLAN, an input-output model to estimate the economic impact of biofuel industry. For this study, important changes were made to the BioFLAME model. The modified model uses the same pool of industrial park candidate facility locations with the addition of medium to large sized sawmills thus increasing the number of candidate facilities across the southeast. The amount of feedstock available is adjusted based on the analyzed scenario. Each spatial hexagon is assigned an amount of available logging residues and mill wastes located within its boundary. The proportion of tonnage of biomass in each hexagon is calculated. The model identifies the location of facilities by minimizing the total feedstock costs. A feedstock least cost analysis is constructed to site economically feasible facilities. Results show a total potential of 68-sited biorefineries with an annual biomass demand

of 50 million dry tons. The top ten sited biorefineries are located in Louisiana, South Carolina, Georgia and Arkansas. The total annual feedstock demand is 7 million dry tons with a total feedstock cost of $2 billion. Each biorefinery on average expends about $22 million and $7 million on feedstock and transportation, respectively. The model ranks biorefineries based on the estimated lowest feedstock cost. Assuming a 100% availability of mill wastes, rank #1 sited facility is located in Winn, Louisiana. This site needs about 4 million truckloads of feedstocks yearly. The total estimated emission is 32 tons of NO_x and 3,277 tons of CO_2. The traffic flows and transportation emissions are highest in Marion, Georgia. Moreover, reducing the mill waste availability to 50% and 10%, the number of sited facilities decline to 34 and 5, and the rank #1 facilities shift to Brantley, Georgia, and Tuscaloosa, Alabama, respectively. Meanwhile, the estimated total annual industry output of biofuel in the region is $22 billion, of which, the value addition is about $11 billion. The biofuel economic activity brings an estimated additional 132,000 workers into the regional economy. Moreover, the biofuels conversion facilities, Bureau of Economic Analysis (BEA) region #42 (Texas and some part of Oklahoma) has the highest estimated total industry output of $884 million. At the sectoral level, impact is highest on the construction of other new nonresidential structures sector.

Introduction

In the U.S. where economy is largely built on transportation systems, access to clean and low-cost transportation is vital (Bartuska, 2006). This development nonetheless, did not come without a cost. Concerns over climate change and fossil fuel availability, and environmental sustainability are at the forefront of discussions among implementers, policy makers and researchers. Consequently, the growing utilization of bioenergy to reduce greenhouse gas (GHG) emission had been examined as life cycle analysis differs between and among types of biomass and conversion technologies that affect environment and energy performance (Cherubini et al., 2009). FitzPatrick et al (2010) cited that the use of renewable energy leads to sustainable development, and that petroleum reliance in transportation increases vulnerability of supply and price spikes (Neufeld, 1999) and affects environment and economy (Dwivedi et al., 2009). Since the 1990s, the U.S. GHG emissions have increased. The U.S. Environmental Protection Agency (2014) recorded GHG emissions: 30% in electricity, transportation 26%, industry 12% and agriculture 9%. Of the total petroleum consumption, about 28% were expended to transport people and goods (US-EIA, 2015). One-third of the U.S. carbon dioxide emissions are linked to the transportation sector contributing to climate change issues (Neufeld, 1999). The increased atmospheric GHGs increase health risk by affecting food and environment (USGCRP, 2016). Despite the number of scientific findings on climate change (Haines et al., 2006), the ability to evaluate the effects on health and risks vary across regions (USGCRP, 2016). Recently, some energy and transportation sectors are transitioning to low-carbon technologies (Wear and Coulston, 2015). This transition is partly due to the decline in cost of conversion technology, price fluctuation of petroleum (Herzog et al., 2001) and government requirements. Two

strategies had been proposed to address climate change, namely: adaptation[8] and mitigation[9]. Forests are considered carbon sink, storing carbon as tree biomass and a valuable resource that can help alleviate the problem of climate change. The amount of biomass as stored carbon increases as trees grow in size and volume (Somnath, 2014). Although climate change altered forest species composition (Ciccarese et al., 2011), forests could potentially offset about 9% (Wear and Coulston, 2015) to 11% of carbon emissions (Depro et al., 2008; US-EPA, 2014).

The demand for woody biomass for bioenergy is increasing under the Energy Independence and Security Act of 2007 and technology development (He et al., 2016). Under the law, the Renewable Fuel Standards (RFS) program requires 16 billion gallons of cellulosic biofuels by 2022 (US-EPA, 2014). As a result, the program indirectly created a biofuel market and reduced risks on biorefinery capital budgets. The RFS necessitates fuel blenders to mix biofuel with fossil fuels (Schnepf and Yacobucci, 2010). Additionally, agencies are directed to reduce annual petroleum consumption by 20% and increase 10% in alternative fuel use (Sissine, 2007).

There are several sources of available renewable energy: Wind, solar, hydropower, geothermal and biomass. These resources exist and are abundant. Increasing the use of renewable energy propels economy, improves environmental conditions, and enhances energy security (USDA, 2006), reduces GHG emissions (Langholtz et al., 2016) and diversifies energy markets supply (Herzog et al., 2001). Worldwide, the supply of renewable energy ranged from 15%-20% of the total energy demand (Herzog et al., 2001). At present, more than half of the renewable energy production in the U.S. is in electricity generation (US-EIA, 2015). The

[8] Adaptation refers on how society able to adjust to minimize harmful effects or take advantage of opportunities on climate change (US-EPA, 2014)
[9] Mitigation is a strategy on reducing fossil fuels use and increasing utilization of renewable energy (Haines et al., 2006)

biofuels consumption doubled from 2000 to 2015, and is projected to grow through 2040 because of government incentives (US-EIA, 2015) and economic growth (IER, 2016). Wood is still the largest bioenergy resource (NREL, 2016; Renewable Energy World, 2017). Other biomass comes from agricultural crops, grasses and woody plants, residues from agriculture and forestry, algae, and the organic component of municipal and industrial wastes (NREL, 2016; He et al., 2016; Galik et al., 2009). Presently, sugarcane and corn biomass are the most important transportation fuel feedstock with more than 40% share each worldwide (World Watch Institute, 2016). Domestically, the transportation sector uses about 10% of ethanol (Bartuska, 2006; Dwivedi et al., 2009) mostly from corn (US-DOE, 2016). However, the problem with corn-based ethanol lies on the uncertainty whether it can efficiently reduce GHG emissions and does not compete for food and animal feeds.

On the other hand, the use of woody non-merchantable biomass and logging residues for bioenergy is rapidly growing (Klavina et al., 2014) because of the sizeable economic prospects (USDA, 2006). Forest removals are an integral part of forestry (Forest Stewards Guild, 2016) and forest productivity is essential to optimize harvesting of biomass and timber (Coyle et al., 2016). In 2015, blended biofuels consumption was roughly 5% ethanol as an additive that increases engine performance and reduce pollution (NREL, 2016). However, there are complex issues concerning forest biomass utilization that must be addressed through integrated programs (Bartuska, 2006). For instance, woody biomass is seldom utilized because of high harvesting and transportation costs, and the difficulty of converting biomass (Rentizelas et al., 2009) into biofuels (Herzog et al., 2001). Improving the availability of feedstock supply is important to bioenergy advancement (Harrill, and Han, 2012). Competitive cellulosic biofuel production

requires reliable feedstock quality (Langholtz et al., 2016) and improved technology (Graham et al., 2000).

There are two primary pathways to convert lignocellulosic biomass to ethanol: Biochemical and thermochemical processes (Lambert et al., 2016). The US-DOE (2016) described biochemical process as a pretreatment to release hemicellulose sugars followed by hydrolysis to break cellulose into sugars while thermochemical technology uses wood chips to convert ethanol through a solid and gas-phase reactions (Foust et al., 2009; Lambert et al., 2016). Despite the cheaper cost of the biochemical process, thermochemical-based technologies are more cost-efficient in converting cellulosic biomass to ethanol (Dwivedi et al., 2009). It is possible to achieve 80-90% thermal efficiencies from advanced gasification (Zafar, 2014).

The study aims to simulate potential site of economically feasible biorefinery locations and the associated cost of feedstock, and to estimate the economic impact of biofuel industry in the southeastern region of the U.S. The Biofuels Facility Location Analysis Modeling Endeavor (BioFLAME), a Geographic Information System (GIS)-based transportation optimization model is designed to simulate feedstock availability and potential site biorefinery locations.

Siting biorefinery facilities and feedstock availability

GIS is an important tool in spatial analysis because it can store and retrieve data, and display maps (Noon and Daly, 1996). The technology combines spatial methods and evaluates constraints (Stewart Fotheringham and Rogerson, 1993), and identifies dataset spatial correlations (Voivontas et al., 1998). Over the years, the advances in GIS technology were developed to analyze complex spatial data (Graham et al., 2000). For instance, it can calculate yield variability, exact transport distances, and costs of feedstock (Rentizelas et al., 2009). The road network is the typical mode of moving feedstock to the biorefinery (Graham et al., 2000).

However, finding optimal biorefinery sites relative to biomass supply is a problem because oftentimes the first facility offers a lower price than the next (Panichelli and Gnansounou, 2008). Graham et al (1997) examined short rotation woody crops supply-cost curves on delivered chips, facility location and feedstock demand in Tennessee. They developed a site-specific cost-curve decision support system to calculate prices of delivered wood chips given the road network, farm gate prices and available supply. Results indicated that feedstock costs greatly differ by location, and increased from 18% to 29% as feedstock demand and transport costs increased. Moreover, Graham et al (2000) modeled a regional GIS-based system to estimate the potential biomass supply of energy crops. Spatial geographic variations in feedstock costs, supply, production areas, yield, and transportation were embedded in the model. They found that transportation costs increase with increased in facility demand, and the delivery cost increased from $33 to $55 per dry ton to supply a facility with an annual capacity of 100,000 dry tons of biomass. Additionally, Panichelli and Gnansounou (2008) analyzed the biomass energy facilities location-allocation using a GIS-based least cost decision support system. They revealed that costs of feedstock vary based available forest biomass and site of facilities.

Data and Data Sources

This study encompasses 16 southeastern states of the U.S. The acquisition of woody biomass was not constrained by political boundaries and potential biomass feedstock located near the boundary of the neighboring states are included in the analysis (Wilson, 2009; Wilson et al., 2011). Data on timberland acreages, annual volume of tree growth per acre by forest stand type, ownership, volume and yield of logging residue and non-merchantable were obtained from the estimated Forestry Inventory and Analysis (FIA) database, and were aggregated at the county level. FIA conducts periodic assessment on forestland condition, volume, growth and removals

of timber as part of the Forest Health Monitoring (O'Connell et al., 2014). The potential supply of logging residues at the POLYSYS level was estimated using the Forest Simulation Economic Analysis Model (ForSEAM), a linear cost minimization model. The data on logging residues costs of harvesting, stumpage and chipping, and the list of 2011 sawmills at the county level were obtained from U.S. Forest Service. Additionally, a county level mill wastes data were also obtained from the USDA-Forest Service-Timber Product Output. The spatial data were obtained from the updated Environmental Systems Research Institute to analyze spatial geographic features of infrastructure features like roads, railroads, waterways, cities, and political boundaries. Two important assumptions used in the study: a) No new road building, and b) buffer zones are set to 50 feet for timberland acres available around the wetland (type F & D) rivers and 25 feet around smaller perennial streams.

Methods

Two models were used; a) BioFLAME model to simulate the least cost feedstock procurement and site of potential biorefineries, and b) Impact Analysis for Planning (IMPLAN) model to estimate the economic impact of biofuels activity in the Southeast. BioFLAME is based on the earlier work of Wilson (2009) and Wilson et al (2011), a Geographic Information Systems-based transportation model to site of economically feasible biorefineries and locate the cheapest source of the biomass supply. The FIA estimated data on timberlands were compared with the 2015 NASS cropland data layer to assess hardwood, softwood and mixed stands density across the Southeast. A high-resolution remote sensing NASS cropland data layer was used to evaluate timberland cover, biomass yield and timber acres available in the region. The ForSEAM model assessed the logging residue tonnage at the POLYSYS region. The stumpage, harvesting and chipping costs of biomass were updated. The model solved by minimizing the total costs of

harvesting and stumpage subject to several constraints, and simulated the shadow prices at varying supply of biomass (Langholtz et al., 2016). The total estimated amount of logging residues and mill waste supply was incorporated into the BioFLAME database. ESRI transportation data containing important geographic features were overlaid on the southeastern map to route trucks through the transportation network. Forest spatial location and existing location of bioenergy facilities, and acres being accessible and located near road network, and those timberlands with slope ≤ 40% were evaluated. "The modeling system allows the analysis on any combination of counties within the 16 southeastern states using geographic features and parameters such as biorefinery capacity, biomass prices, yield and availability, transportation cost, driving distance and expected profit where a potential biorefinery might be located near or away" (Wilson et al., 2011). Several significant changes were made to the energy crop version of BioFLAME to allow the model to utilize logging residues and mill wastes (Figure 12). However, no changes made in the land cover, and the breakeven price was not calculated rather the model simply selects forest logging residues and mill wastes to minimize biomass procurement and transport costs. Details on the technical methods were described in Wilson (2009). Below are the description of input data utilized in BioFLAME:

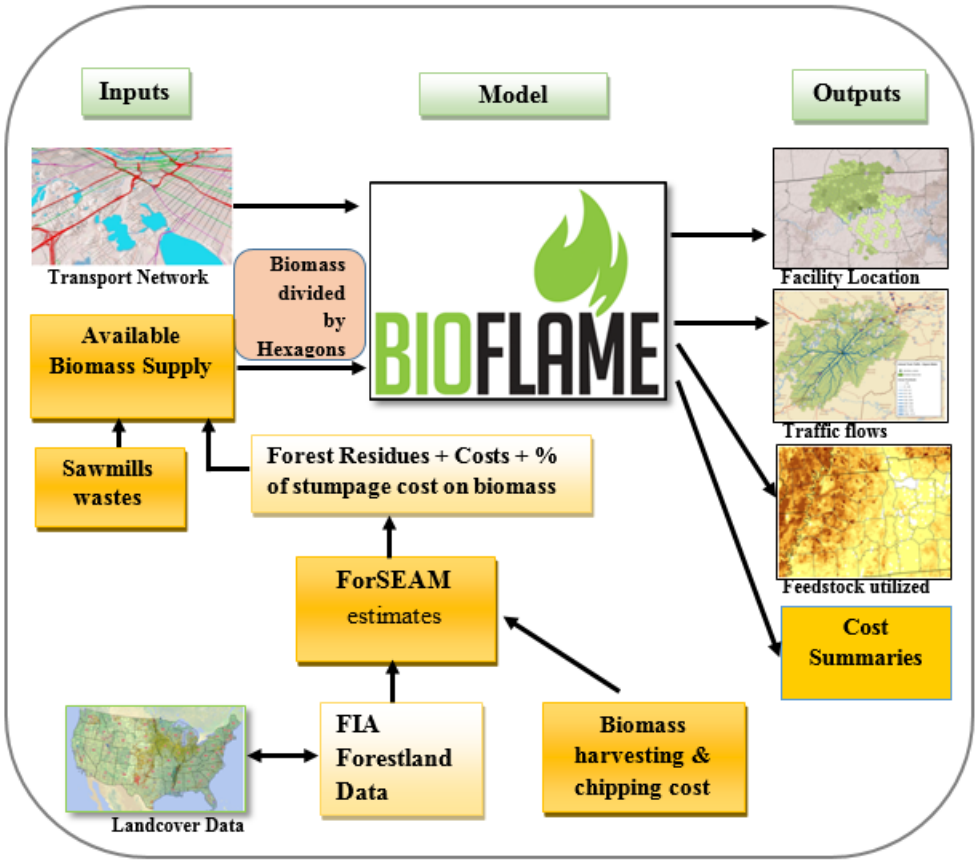


Figure 12. Modified BioFLAME model using logging residue and mill waste feedstock

Potential Biorefinery Sites

Industrial Parks

Several industrial parks are located within the Southeast. Industrial parks are areas zoned for heavy industrial use such as manufacturing, oil-refineries, airports, sawmilling, among others. Considering the magnitude of the real world industrial parks present in the region, the study selected a few industrial parks that are potential candidate nodes (centroids of spatial hexagons). The selection of candidate nodes was based on the suitability assumptions: water and electricity utilities availability and proximity to market

centers and major road network. The same pool of industrial park candidate facility locations was used and medium to large sized sawmills were added to the model, bringing the total number of candidate facilities from 462 to 1,153 across the Southeast (Figure 13).

Sawmill Locations

There are 1,055 sawmills located throughout the Southeast region at the county level (Figure 14). These sawmills provide potential mill wastes for the sited biorefineries. Sawmills were grouped and classified based on the milling capacity size. The sawmills with capacity size of 3, 4, 5, and 6 with midpoint (average) capacity of 1851, 4000, 9150 and 16500 thousand board feet (mbf), respectively were included in the analysis. However, those sawmills with capacity size 1 and 2 mbf (<200 to 1,000 mbf) were excluded because of the limited mill wastes available. Similarly, the total mill wastes supply at the county level was also calculated. A simple regression analysis was performed to estimate the total mill wastes supply. Mill wastes were estimated as a function of sawmill capacity size. The resulting regression coefficient was multiplied to the amount of mill waste at the county level. The total mill wastes data were aggregated, and data units were converted from green tons to dry tons assuming a 55% moisture content.

Potential Feedstock Location

The forestland cover and available logging residue supply in southeastern region were downscaled into equal hexagons consisting of 5-square mile area. The concept of a hexagon as a geographical unit of analysis is central to the BioFLAME (Wilson et al., 2011; Lambert et al., 2016). “Hexagonal grids are simpler and more efficient coordinate systems than rectangular

grids in locating the nearest neighborhood connections" (Birch et al., 2007). A 30-meter pixel level, high-resolution remote sensing cropland data layer was used to assess the location of the forest cover (hardwood, softwood and mixed) in the Southeast. Both the forestland acres and the ForSEAM estimated logging residues supply at the POLYSYS region were broken down and assigned in each hexagon. The available woody logging residues located within the boundary in each hexagon were linked through hexagon pixel counts and ids. The available tonnage of logging residues for each hexagon was calculated as the ratio of the ForSEAM estimated logging residues and the amount of forest biomass in the cropland data layer.

Mill sites

A hypothetical "what if" scenario was constructed to simulate potential available mill wastes at 100%, 50% and 10% for bioenergy. These mill sites are potential sources of biomass of the sited biorefineries in the South. While at present, most of the mill wastes are utilized for the production of fiber and paper products and as on-site energy needs, about 1.5% of primary mill wastes (Perlack et al., 2011) and 40% of secondary mill waste (Perlack et al., 2005; Langholtz et al., 2016) could be available at the different mill sites. The number of potential mill sites varies supplying biomass to the biorefineries from 92 mill sites to 543 potential mill sites (Figures 15, 16 & 17).

ForSEAM Projections

The FIA data on timberland were simulated using ForSEAM to estimate biomass supply. The simulation period ran from 2014 to 2055. At the onset, ForSEAM used the U.S. Forest Product Model (USFPM) projections on the conventional timber product and biomass feedstock demand as exogenous demand level. The model solved first the conventional timber demand prior to estimating the supply of biomass (Langholtz et al.,

2016). Then, it simulated the total availability by calculating first biomass supply of the previous period then the next period and so on. The biomass supply targets were varied from 1 million to 300 million dry tons at 1-million dry ton increment to obtain shadow prices and plot the supply of available residues to meet feedstock demand.

Feedstock costs

Avila (2017) simulated the FIA data with ForSEAM. The resulting estimated logging residues were allocated to each forested pixel. The biomass stumpage and harvesting costs based on the 2014 RISI report were calculated and aggregated at the POLYSYS level (Langholtz et al., 2016). For each hexagon, a ratio for stumpage, harvesting and chipping was calculated. The total cost of delivered logging residues was calculated as the sum of stumpage, harvesting, chipping and other costs plus transportation. Delivered cost of mill waste feedstock was calculated as sum of the on-site sawmill price per ton and transportation.

Stumpage Price

An updated RISI report on pulpwood price was used as stumpage price for both hardwood and softwood class 2 stands. On logging residues price, stumpage price was estimated as a fraction of whole tree stumpage price based on the yield proportion of whole tree to logging residues (Langholtz et al., 2016). The assumed stumpage price for sawtimber (Class 1) is twice that of pulpwood (Class 2), Class 3 stumpage price is 50% less than pulpwood (Langholtz et al., 2016). Mixed stand was calculated as 37.5% of the hardwood stumpage price plus 62.5% of the softwood (Langholtz, et al., 2016).

Harvest/Collection Costs

Chipping and stumpage fees vary depending on the type of biomass and the method of harvest utilized. Collection of logging residues was integrated with the

conventional timber product harvesting. Standard conventional timber harvest consists of felling, skidding, delimbing and loading (Langholtz et al., 2016). Collecting logging residues however, requires an extra cost to cover the additional chipper and extra loader attached to the conventional timber equipment harvesting system (Langholtz et al., 2016).

Transportation of Chipped Material Costs

The logging residues were chipped in van at the roadside. These chip residues were transported using trucks within the restricted 75-square mile distance from the source to the sited biorefinery. The model assumed a user-defined transportation cost of feedstock on per ton per mile basis (Wilson, 2009).

In siting facilities, a feedstock least cost analysis was constructed to calculate the total feedstock cost and average cost per dry ton surrounding each potential site. The model iterated by minimizing cost of delivered feedstock to the biorefinery. Ideal biorefinery sites were selected based on the feedstock lowest cost. The total annual feedstock cost was calculated as the sum of the acquisition of biomass feedstock plus the transportation cost. The transportation costs were calculated by multiplying the user-defined cost per dry ton per mile by the shortest route from the source to biorefinery (Wilson et al., 2011). Each sited biorefinery located within 75-square mile driving distance limit and along with the specified geographic features was ranked. Those biorefineries located in “far or within” the undesirable geographic features were removed. Assuming a capacity goal of 700,000 dry tons each candidate node was iterated and evaluated. For multiple sited biorefineries, each facility was sited in sequence from best location then next best location and so on (Wilson et al., 2011). When a biorefinery is sited, “the associated lowest cost feedstock is labeled as unavailable for the next facility in the line forcing the next biorefinery to look for feedstock elsewhere” (Wilson et al., 2011). The cheapest feedstock cost

combination is found in locations where transport cost is minimized (Lambert et al., 2016). Finally, the annual feedstock cost summaries were generated for the 3 mill waste supply scenarios.

The IMPLAN model was used to determine the economic impact of biofuels activity in the economy of the region. The model estimated the total industry output, employment, labor income and total value added particularly on the direct, indirect, and induced economic impacts (He et al., 2016). IMPLAN is an established and widely used input-output model to estimate economic impacts either at national, regional or county level. The model was used extensively in several studies concerning regional economic impact analysis such as outdoor recreation expenditures for state parks (Bergstrom et al., 1990), hospitality and tourism (Bonn and Harrington, 2008), recreational fisheries (Steinback, 1999), woody biomass utilization (Perez Verdin et al., 2008), agricultural crops and forestry (Menard et al., 2013; Hodges and Spreen, 2006) and bioenergy and biofuels (Lambert et al., 2016). In this study, IMPLAN key assumptions on sectoral impact variables were updated based on an annual production capacity of 56.6 million gallons or 2,000 metric tons per day or approximately 700,000-dry ton capacity of biomass per year (Wright et al., 2010). Biomass moisture content is roughly 10% of weight and less than 1% ash content. In the model, sectoral variables particularly the capital investment and annual operational costs (including depreciation) were updated using the most recent cellulosic biomass fast pyrolysis technology based on the published Techno-Economic report of the National Renewable Energy Laboratory (Wright et al., 2010). Similarly, economic values on grid electricity credits, transportation costs, labor income, Renewable Identification Number (RIN) and chipping were also updated and embedded in the model. These variables are essential in estimating the total economic impact of biofuel activity in the region. For instance, the total

feedstock transportation cost for each biorefinery was calculated by taking the ratio of transportation cost divided by $10 million multiplied by the number of biorefineries. The same calculation was applied to estimate chipping cost and proprietor's income per facility. Total economic impact monetary values were inflated to 2017 dollars.

Results

Siting of Biorefinery Facility

A total of 68 potential biorefineries are sited and distributed throughout the 11 Southeastern states (Figure 18). The state of Georgia, Mississippi, North Carolina, Alabama, South Carolina, Arkansas and Virginia each has at least 5 sited biorefineries while Tennessee, Florida, Louisiana and Kentucky have fewer than 3 potential facilities. Georgia has the highest number of sites with 13 sited potential biorefineries while Kentucky has one facility. Biorefineries in Georgia require 10 million dry tons of biomass feedstock of which 80% are mill wastes mostly from large capacity sawmills (Figure 21). This is about 21% of the total potential feedstock available in the south. The top 10 locations of sited facilities are concentrated in four states: Georgia, South Carolina, Louisiana and Arkansas with an estimated biomass demand of 7 million dry tons (Table 12). These sited biorefineries are ranked based on the total feedstock cost where rank #1 as the cheapest. Ranking is important among investors in deciding biofuels investments. For instance, sited facility in Winn, Louisiana has the lowest annual total feedstock costs while Marion, Georgia registers the highest. The facility in Winn, Louisiana requires an annual feedstock supply of 702,655 dry tons with 53% mill wastes. The total annual feedstock cost is estimated at $28 million with $21 million dollars (77%) as biomass acquisition cost. Feedstock average cost is $46 per dry ton. In contrast, Marion, Georgia (rank #68) needs about 903,124 dry tons of biomass supply. Majority (98%) are mill wastes and 2% logging residues.

The total annual feedstock cost is $37 million, 74% of which is feedstock acquisition. Transportation cost is 25% higher than rank #1 facility. Generally, mill wastes are the primary sources of biomass feedstock. Larger capacity sawmills provide most of the biomass to the biorefineries except those located in Tennessee and Kentucky (Figure 21). This suggests that with an increase demand of conventional timber products, supply of mill wastes and logging residues also increase. When mill wastes supply reduces to 50% and 10%, sited biorefineries locations change substantially (Figures 19 & 20). Rank #1 biorefineries shift to Brantley, Georgia and Tuscaloosa, Alabama at 50% and 10% available mill wastes, respectively. At 50%, about 34 facilities are sited with a total estimated feedstock cost of $1 billion annually. Sited facility in Brantley, Georgia has an annual feedstock cost of $28 million and Laurens, South Carolina with $33 million. Further, at 10% mill wastes available, sited facilities shrink to 5 locations and the total annual feedstock costs of $156 million. The highest ranked biorefinery site shifts to Tuscaloosa, Alabama (rank #1) with a feedstock cost of $31 million, an increase of roughly 11%. The highest feedstock cost is sited in Amelia, Virginia (rank #5). On the other hand, the model has sited 2 potential biorefineries that have the same exact location in Clark, Arkansas (Figures 18 & 19). Similar situation is also shown in Winn, Louisiana where two sited biorefineries are closely located to each other (Figure 18). Thus, a better option for these facilities is to consolidate into a larger capacity biorefinery to accommodate twice the amount of biomass and possibly double biofuels production. A bigger biorefinery not only withers competition of feedstock acquisition, optimizes biomass supply, reduces cost of procurement and minimizes traffic flows and air pollution but also reduces the cost of capital investments. Furthermore, at 100%, 50% and 10% mill wastes, the model sited one infeasible facility #69, #35 and #6, respectively in Loudon, Virginia because of the border effect (Figures 18, 19 & 20). The

site is located near the border and some of its feedstock supply come from West Virginia (Figure 23). This facility is infeasible because the amount of feedstock available is not adequate to support a biorefinery with a 700,000 dry tons feedstock requirement. Extending the analysis to cover West Virginia and other neighboring states may somehow improve the feasibility of the sited facility as there may be available biomass within the set buffer distance.

Feedstock and cost analysis

100% mill wastes available

The potential biomass feedstock and costs are analyzed in Table 12 & Figure 18. Fifty (50) million dry tons of woody biomass are potentially available in the South (Table 12). About 80% of the woody biomass are mill wastes and 20% logging residues. Softwoods provide the majority (50%) of the logging residues. Each biorefinery requires an average of 731,189 dry tons of biomass every year. Mill wastes propel biofuel production in the region as these facilities are dependent on its supply, primarily because most sited biorefineries are closely located along with existing sawmills' facilities. These sawmills are often situated close to major roads, thus lower the cost of transportation. In contrast, the lack of adequate supply of logging residues could be either due on the 5% harvest restrictions or logging residues are situated farther away from the 75-square mile distance limit. Costs vary depending on the sited facility location, distance and the biomass sources. Total annual feedstock cost of the 68 biorefineries is estimated at $2 billion, of which biomass acquisition accounts 76% and transportation 24% (Table 12). Feedstock costs range from $50 to $53 per dry ton. The total annual feedstock costs range from $28 million to $37 million with an average cost of $29 million. Stumpage accounts 7%, chipping 23%, other costs 19% and cost of mill wastes 48%.

50% mill wastes available

The 50% reduction of available mill wastes has changed considerably the sites of biorefineries (Figure 19). The total available biomass supply is 24 million dry tons. As shown in the figure, 34 biorefineries are sited. Rank #1 biorefinery is sited in Brantley, Georgia with a feedstock cost of $28 million and biomass requirement of 709,238 dry tons (Table 18). Conversely, rank #34 facility is in Laurens, South Carolina. The total feedstock cost is $33 million, a 14% higher than rank #1 facility. The transportation expense is almost doubled. Despite the 50% reduction, mill wastes remain an important feedstock (65%) and 35% logging residues (Figure 24). Softwoods contribute 17% of the logging residues.

10% mill wastes available

At 10% available mill wastes, sited biorefineries further shrink to 5 facilities (Table 14). Locations of facilities have also changed considerably. Rank #1 facility shifts to Tuscaloosa, Alabama with an annual total feedstock cost of $31 million. Of the facility demand of 701,555 dry tons of biomass, 35% are softwoods, 28% are mixed woods, 23% are mill wastes and 14% are hardwoods (Figure 28). Biomass acquisition cost is 70% and transportation accounts 30% of the totals. In contrast, biorefinery in Amelia, Virginia shows the highest feedstock cost ($31.9 million), roughly 4% higher. Of the three mill wastes scenarios, the 10% supply available indicates the highest feedstock transportation costs.

Traffic flows and transportation emissions

Traffic flows and emissions are positively related suggesting that as the traffic volume increases, transportation emissions rise. Truck emissions are influenced with facility distance and biomass source and slope of the road. Of the 68 sited biorefineries, 3 locations (sites #1, #5 and #68) are examined to compare differences on the traffic flows and emissions. Site #1 (Winn,

Louisiana) being the lowest feedstock cost and Marion, Georgia (site #68) with the highest cost. Most biorefineries obtain feedstocks locally from different locations within the 75-square mile area. For instance, rank #1 procures mill wastes from 4 nearby sawmills, and its logging residues are sourced across different landing sites around the 75-square mile buffer distance from the facility (Figure 24). Sawmills are mostly located in "brown bag" areas which means within the industrial zones. They are also located along the dark-colored 5-square mile area hexagons indicating more available feedstocks supply. As can be seen on the figure, traffic flows between sawmills and biorefinery are denser due to the volume of truckloads transporting feedstocks passing on the same road route compared to logging residues. This suggests that mill wastes feedstock is crucial to the biorefinery operations. Logging residues are transported by smaller truckloads, and at some point, trucks converge in major roads leading towards the sited bioefinery. A total of 4 million truckloads or about 8 million truck volume passes back and forth on the same road routes (Table 19). Total annual cumulative distance truck traveled is roughly 2 million miles. Mill wastes have shorter transport distance than logging residues to the biorefinery. Over the year, the expected total annual emissions is 32 tons of NO_x and 3,277 tons of CO_2 (Table 19). Similarly, the feedstock transport distance in site #5 is slightly shorter than site #1 (Figure 25). Its emission is also lower. As can be seen on the figure, the feedstock supply of the biorefinery come from the 3 sawmills while the supply of logging residues are located mostly from northwestern side of the sited biorefinery as indicated by darker color hexagons. Traffic flow from sawmills to the biorefinery are dense. Of these sawmills, 2 sawmills are located close to the sited #5 facility. The other sawmill is located father away but the traffic flow is heavier implying that this mill site provides most of the required biomass feedstock (Figure 25). The total truck volume is estimated at 6 million a year. Traffic volume is denser in road

routes from sawmills to biorefinery than logging residues where transport is through smaller truckloads. Compared to site #1 facility, trucks mileage, NO_x, CO_2 and other particulates are approximately 10% lower. Finally, the highest traffic flows and emissions incurred is with site #68. These emissions are attributed to the distance of feedstock source (sawmills) to the to the biorefinery (Figure 26). About 98% of the feedstock supply are mill waste supply coming from the 4 sawmills' facilities. Traffic flows are dense and truck volume is high. About 5 million truckloads annually with a total cumulative truck distance of 2.5 million miles. Emissions contribute approximately 44 tons of NO_x and 4,437 tons of CO_2 per year. These amount of emissions and particulates are additions to the existing level of pollutants in the atmosphere. Over time, these NO_x, CO_2 and particulates can have significant implications on respiratory health and air quality.

Economic impact in the Southeast

Analysis on the cellulosic biofuel industry economic impact on total industry output, employment, labor income and value addition are shown in Table 17. Investing in cellulosic biofuels creates sizeable economic impacts in the region. As can be seen on the table, the estimated total industry output is $22 billion. The direct output value attributed to biofuel activity is roughly $13 billion (59%). The impact of investment on biofuels conversion facilities constitutes to the total industry output is the largest (22%), amounting to $9 billion. The economic impact of feedstock (chips) utilization is estimated at $37 million and trading of Renewable Identification Number (RIN) that tracks the biofuel movement from the biorefinery to blending facilities is $2 billion. Moreover, biofuels activity indirectly affect the input suppliers and other backward industry linkages at an estimated $4 billion. Biofuel production brings about 132,000 total employments in the economy. Specifically, its impact on direct, indirect and

induced employment brings 66,700 workers, 28,300 workers and 36,900 workers, respectively. This economic impact could increase household's disposable income and expenditures as it generates more wealth in the economy. The gross domestic product is estimated at $11 billion of which labor income (includes proprietor's income, salaries and wages, other type income and indirect taxes) accounts $8.7 billion or 76% of the value addition in the economy. The Southeast has 37 Bureau of Economic Analysis (BEA) regions (Table 18). Each BEA region cuts across different states. Evaluating closely on the potential total economic impact of biofuels, BEA region #42 (Texas and some part of Oklahoma) has the largest. The total estimated industry output is $888 million involving 49,000 potential workers. Its estimated gross domestic product is $490 million and labor income accounts 73% ($361 million). The top five largest sectors effected with biofuel investments are shown in Table 19. The total industry output is $363 million. The sector on construction of other new nonresidential structures has the largest economic impact of $162 million. Total value addition to the economy is $171 million and about 1,905 potential workforce. Labor income accounts 86% of the gross domestic product. Similarly, the feedstock (chips) total industry output is minimal. An estimated impact of $1 million, of which $566 thousand (46%) effect the sector on commercial and industrial machinery and equipment repair and maintenance (Table 20). The total value addition to the economy is roughly $857 thousand. Nonetheless, its economic impact on employment is marginal.

Discussion and Conclusion

The total timberland acres in conterminous U.S. is about 488 million. About 41% are in the south (202 million acres) comprising hardwood (22%), softwood (15%) and 4% mixed wood. However, when acreages are restricted within the 1-mile road harvest distance (196 million acres), changes in the distribution of timberland acres are sizeable (mixed wood is 23%,

softwood 16%, and hardwood 5%). This indicates that hardwoods are mostly located in areas farther away from the road network. Thus, logging residues available for harvest in the south are mostly softwoods and mixed. Logging residues and mill wastes are potential biofuel feedstocks. Currently, mill wastes like sawdust, shavings and chips are either used on-site energy or sold as goods. At present, significant amount of mill wastes is consumed on-site for heating and power. Other uses include animal bedding, landscaping, pulp and raw materials for fiberboard and particleboard production (Setunge et al., 2009; Loeffler et al., 2016). While sawmills consume several types of combustion power in the operations, 77% of mill wastes are primarily utilized for heat and steam in lumber drying, and building heating system (Maker, 2004). Further, Maker (2004) cited that combined heat and power is possible using mill wastes with new biomass gasification equipment. However, cellulosic biofuels market and improve biomass prices must be developed so that sawmills sell its mill wastes to biofuel facilities rather than consume on-site for energy. In addition, prices of natural gas must be low enough to attract sawmills to switch on-site energy consumption.

The development of cellulosic biofuels is currently at the forefront due to concerns on environmental sustainability. At present, most of the ethanol produced are from corn and sugarcane. The Energy Independent and Security Act of 2007 mandates the production of ethanol from cellulosic biomass. The expanded Renewable Fuel Standards program, capped the 1st generation ethanol to 15 billion gallons (Schnepf & Yacobucci, 2010). Thus, the utilization of logging residues and mill wastes as 2nd generation cellulosic ethanol can provide substantial amount of biomass to propel bioenergy. Lambert et al (2016) cited that 10.5 billion gallons can be potentially produced in the south. This is about 57% of the total 16 billion gallons total cellulosic biofuels in the US. However, technologies that convert cellulosic woody biomass are

currently evolving. Despite government incentives, investments on cellulosic biofuel production remain low and very few investors are interested to pioneer investments due to huge capital investments, expensive conversion technologies, and technological risks and obsolescence. In most cases, pioneering facilities are later outweigh with new and efficient technologies. Cellulosic biofuel production from woody biomass is new and the available technology may not be efficient. Currently, fast pyrolysis technology is considered one of the most efficient technologies that convert cellulosic biomass to biofuels (Wright et al., 2010). Correspondingly, siting of biorefinery optimal location can be challenging relative to biomass total feedstock cost and availability, and product and by-product markets (Lambert et al., 2007). Logging residues are potential cellulosic feedstock for bioenergy. However, biomass market and prices must be at par with other established feedstocks to encourage landowners and contractors to collect logging residues during timber harvest. Additionally, biofuel facilities and feedstock locations must be located closer to major roads to minimize costs of transport (Keefe et al., 2014). The study aims to simulate potential site of biorefinery locations and associated cost of feedstock, and to estimate the economic impact of the industry in the south. The BioFLAME, a Geographic Information System (GIS) transportation optimization model can simulate feedstock availability and site economically feasible biorefinery location. Feedstock and suitability criteria are embedded in the model to screen locations of available potential feedstocks and site of biorefineries within the set of geographic features that minimizes total feedstock cost. These geographic features are near major road network, power lines, urban centers and industrial zones. The model also assumes each facility requires at least 700,000 dry tons annually (Wright et al., 2010). These biorefineries need consistent supply of feedstocks at competitive prices. The model runs on several iterations to estimate available feedstock sources and site of potential

biorefineries. At the onset, the model calculates biomass demand of the 1st sited facility and satisfies its demand before the 2nd, 3rd facility gets their supply and so on (Wilson, 2009). The next lowest feedstock cost and site within the 75-square mile driving distance is calculated until all available logging residues and mill wastes are allocated. The model assumes that the total feedstock cost of the first sited facility is lower than biomass sourced from the neighboring counties. Several significant changes are made from the previous energy crop version of BioFLAME to allow the model to utilize forest residues and mill wastes. Though the same pool of industrial park candidate facility locations are used, medium to large sized sawmills are added, bringing the total number of candidate facilities to 1,153 across the southeast U.S. In the earlier version, supply database contains the land cover breakdown for each hexagon crop zone, however, for the logging residues and mill waste version, each hexagon is assigned an amount of available softwood, hardwood, or mixed forest logging residues and mill wastes if sawmills are located within the boundary. The assessment of logging residue tonnage is done using the ForSEAM and cropland data layer. There are no changes made in the land use and breakeven price is not calculated rather the model simply selects forest residue and mill wastes in a way to minimize procurement and transport costs. The amount of mill waste available at the mills is adjusted depending on the scenario. With 100% mill wastes available, results show 68-sited potential biorefineries located throughout the south. These facilities require about 50 million dry tons of woody biomass. The sited biorefinery in Winn, Louisiana is ranked #1 with the lowest total feedstock cost of $28 million with biomass acquisition cost constitutes 77% of the total cost. Reducing the mill wastes supply to 50% significantly changes the site of biorefineries and feedstock costs. In this scenario, the sited facility shifts to Brantley, Georgia with a total annual feedstock cost of $28 million. Transportation cost is slightly higher than the 100% mill wastes

available. Further restricting mill wastes supply to 10% considerably shrinks the number of biorefineries in the south. About 5 facilities are sited economically feasible. Rank #1 biorefinery moves to Tuscaloosa, Alabama. The estimated feedstock cost is $31 million, 10% higher compared to 100% mill wastes available. Similarly, highest feedstock cost of $32 million is located in Amelia, Virginia (rank #5). As can be seen on the figure, 72% of the feedstock are logging residues with softwoods constitute about 35%. With the current use of mill wastes, at present, it seems that the 10% mill wastes availability scenario is more realistic considering that mill wastes are used by sawmills as source of on-site energy heat and power.

IMPLAN estimates the total economic impact on biofuel industry in the south. Results indicate that investment in biofuel production has sizeable economic opportunities in the region. The total industry output is $22 billion with 59% directly attributed to biofuel industry. Investment on conversion biomass to cellulosic biofuel facilities has the largest economic impact to the industry. RIN direct output accounts $2 billion. Indirect output is estimated at $4 billion as input suppliers and other backward linkages react with the economic stimuli. The industry's economic direct output on employment generates 132,000 job opportunities in the local economy. The estimated gross domestic product of the industry is $11 billion. However, where sited biorefineries are concentrated in one area, economic opportunities grow. Thus, total industry output, direct, indirect and induced output are expected to increase. Economic transaction leakages are marginal as most economic activities revolve within the local economy. Results of the study can be an important guide for government to create policy actions toward the development of biofuel markets, and elicit biorefinery investments by providing monetary incentives and insure biorefineries of continuous biomass feedstock supply at competitive prices.

Some important caveats in the analysis of results; First, at present, the model is designed for the southeastern region, and expanding the analysis to cover the entire U.S. requires modifications to address complex computer data processing and disk space requirements. Likewise, hexagon sizes are in 5-square mile area to speed up computing where in reality it may be less. Second, analysis relies on the data available. The 2011 list of sawmills does not have data on West Virginia which could have a potential impact on the siting of biorefineries. West Virginia is one of the timber producing states in the southeast, thus affects the regional distribution of the potential sited biorefineries. Third, feedstocks analyzed are limited to forest logging residues and mill wastes. Available logging residues are not adequate and are located farther away from desired geographic features. Meanwhile, mill wastes are currently being used by sawmills on their on-site energy needs. It would be interesting to evaluate simultaneously these feedstocks with other available biomass such as energy crops, short rotation woody crops and non-merchantable whole-tree on the impact on optimal location of sited biorefineries and feedstock costs. Fourth, the estimated total feedstock costs reflect the roadside cost of logging residues and on-site cost for mill wastes, and exclude costs of transportation to preprocessing and blending facilities. Blending and preprocessing facilities are integral infrastructures along the supply chain to maintain stable biomass supply. These facilities reduce costs and improve biofuel logistics. Finally, even though most of the GIS models have the capability to capture spatial geographic variation and calculate biomass feedstock cost and supply, these models at present, are not constructed to handle uncertainty.

Future directions can be focused on including costs of biomass transportation additional facilities such as storage, preprocessing, distribution or blending facilities located within the strategic places like near the airports and urban centers. Preprocessing facilities are important to

process partially woody biomass like bio-oil. Additionally, blending stations provide consumers ready access to biofuels. Second, extend the analysis to the entire U.S. and estimate economic impacts of the biofuel industry. The estimated economic impacts in various BEA regions potentially guide investors in making decision in locating potential cellulosic biofuels investments. Third, integrate in the analysis other feedstocks such as non-merchantable timber, energy crops and short rotation crops to accurately site biorefineries and calculate optimal feedstock cost. Fourth, supply of biomass is within the restricted to 75-square mile road distance. There might be more logging residues supply beyond the 75-square mile distance. Finally, modify the geographic features to include reduction of driving distance buffer to 50-square mile limit and shift the location towards rural areas where most of logging residues and non-merchantable biomass are located.

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Appendix

Table 14. Total annual woody biomass feedstock cost at 100% available mill wastes in the Southeast

Site Number	County	State	Unit Cost	Average Cost	Total Residues	Total Transportation Cost	Total Stumpage Cost	Total Chipping Cost	Other Costs[10]	Total residue Cost	Total feedstock Cost
			$/dry ton		dry tons	Million dollars					
1	Winn	Louisiana	52.7	45.9	702655	6.1	1.4	4.8	4.0	21.4	27.7
2	Georgetown	South Carolina	52.7	45.8	707068	6.7	0.5	2.1	1.7	21.4	28.3
3	Glynn	Georgia	52.7	45.8	713552	6.8	0.6	2.3	1.8	21.6	28.5
4	Effingham	Georgia	52.7	45.2	708177	5.0	0.7	2.9	2.3	21.4	26.7
5	Jeff Davis	Georgia	52.7	45.0	736649	5.4	0.7	2.6	2.2	22.3	27.9
6	Ware	Georgia	52.7	48.9	700883	5.6	0.2	0.6	0.5	21.1	26.9
7	Ben Hill	Georgia	52.7	48.0	715963	6.7	0.4	1.5	1.2	21.6	28.5
8	Laurens	Georgia	52.7	46.3	721598	6.1	0.8	3.1	2.4	21.9	28.1
9	Columbia	Arkansas	52.7	45.3	710593	6.9	1.4	5.1	4.1	21.7	28.7
10	Bulloch	Georgia	52.7	48.5	711678	7.1	0.2	0.8	0.6	21.4	28.7
11	Orangeburg	South Carolina	52.7	44.3	743205	5.6	0.9	3.2	2.3	22.5	28.3
12	Kershaw	South Carolina	52.7	44.7	754237	5.4	1.3	4.8	3.7	22.9	28.5
13	Florence	South Carolina	52.7	48.1	706990	4.5	0.1	0.3	0.2	21.2	26.0
14	Grady	Georgia	52.7	44.5	736480	6.2	1.2	4.4	3.5	22.4	28.7
15	Taylor	Florida	52.7	44.5	704884	5.0	0.4	1.4	1.1	21.2	26.5
16	Jackson	Florida	52.7	45.7	716764	4.7	0.4	1.6	1.3	21.6	26.5
17	Russell	Alabama	52.7	46.9	704239	6.8	1.2	4.3	3.4	21.4	28.3
18	Monroe	Georgia	52.7	46.2	704259	5.5	0.5	2.2	1.7	21.3	27.0
19	Wilkes	Georgia	52.7	44.4	701458	5.1	1.1	4.3	3.4	21.3	26.6
20	Newberry	South Carolina	52.7	45.8	806343	2.4	0.2	0.9	0.7	24.2	26.9
21	McCormick	South Carolina	52.7	50.5	724209	5.3	0.0	0.0	0.0	21.7	27.3
22	Washington	Alabama	52.7	46.1	737356	6.3	0.9	2.9	2.2	22.3	28.8

[10] Includes cost of mill wastes

Table 14. Continued

Site Number	County	State	Unit Cost	Average Cost	Total Residues	Total Transportation Cost	Total Stumpage Cost	Total Chipping Cost	Other Costs	Total residue Cost	Total feedstock Cost
			$/dry ton		dry tons	Million dollars					
23	Clarke	Alabama	52.7	48.5	711379	6.0	0.1	0.4	0.3	21.4	27.7
24	Walthall	Mississippi	52.7	45.5	700312	7.2	1.1	3.9	3.2	21.3	28.6
25	Claiborne	Mississippi	52.7	43.8	705004	6.5	0.7	2.5	1.9	21.3	28.0
26	Union	Arkansas	52.7	47.3	738144	6.6	0.6	2.0	1.7	22.3	29.1
27	Gilmer	Georgia	52.7	46.2	704845	7.5	1.4	4.1	3.1	21.4	29.1
28	Chambers	Alabama	52.7	45.5	721288.5	7.1	0.6	2.7	2.2	21.8	29.1
29	**Clark**	**Arkansas**	52.7	45.9	714066.9	7.4	0.9	3.2	2.6	21.6	29.3
30	**Clark**	**Arkansas**	43.9	37.3	736141.2	5.1	0.0	0.0	0.0	22.1	27.5
31	Conway	Arkansas	52.7	44.5	700916.7	7.0	0.8	2.5	2.0	21.2	28.4
32	Gates	North Carolina	52.7	45.2	703667.4	7.8	0.8	2.8	2.2	21.3	29.3
33	Smith	Mississippi	52.7	44.9	700782.5	8.0	0.6	2.1	1.6	21.2	29.4
34	Madison	Alabama	52.7	46.1	702055.3	8.2	0.7	2.3	1.7	21.2	29.6
35	Patrick	Virginia	52.7	45.3	710740.0	8.0	1.1	3.3	2.5	21.5	29.7
36	Wilkes	North Carolina	52.7	44.3	719795.7	7.0	0.5	1.4	1.2	21.7	28.9
37	Montgomery	North Carolina	52.7	45.3	710056.9	7.3	0.8	2.4	1.9	21.5	28.9
38	Rockbridge	Virginia	52.7	45.9	704957.0	7.7	1.1	2.9	2.2	21.3	29.2
39	Cabarrus	North Carolina	52.6	48.9	708499.3	8.1	0.0	0.1	0.1	21.3	29.6
40	Franklin	Mississippi	52.7	47.8	712150.2	8.1	0.3	1.1	0.8	21.4	29.7
41	Union	Florida	52.7	43.8	818422.8	4.8	0.6	2.3	1.9	24.7	29.8
42	McNairy	Tennessee	52.7	45.2	712854.4	8.0	1.4	4.1	3.2	21.7	29.8
43	Prentiss	Mississippi	52.7	47.1	710355.0	7.9	0.8	2.8	2.2	21.5	29.6
44	Winston	Alabama	52.7	45.7	753073.2	6.6	1.0	3.7	2.8	22.8	29.6

Table 14. Continued

Site Number	County	State	Unit Cost	Average Cost	Total Residues	Total Transportation Cost	Total Stumpage Cost	Total Chipping Cost	Other Costs	Total residue Cost	Total feedstock Cost
			$/dry ton		dry tons	Million dollars					
45	Fayette	Alabama	52.7	45.9	756162.8	6.1	0.8	3.0	2.3	22.9	29.2
46	Pickens	Alabama	52.7	47.4	715904.6	6.3	0.5	1.8	1.5	21.6	28.1
47	Bibb	Alabama	52.7	43.9	744890.8	6.6	0.7	2.5	2.0	22.5	29.3
48	Winston	Mississippi	52.6	44.9	712864.0	7.7	1.3	4.4	3.6	21.7	29.5
49	Warren	North Carolina	52.7	45.4	704825.3	8.4	1.8	5.8	4.5	21.5	30.0
50	Randolph	North Carolina	52.6	45.8	732309.6	6.1	0.7	2.0	1.5	22.1	28.4
51	Pitt	North Carolina	52.7	44.5	701814.6	7.8	0.6	2.1	1.8	21.2	29.2
52	Essex	Virginia	52.7	44.7	728202.2	7.7	1.0	2.8	2.3	22.0	30.0
53	Amelia	Virginia	52.7	44.1	703060.1	7.5	0.7	2.2	1.7	21.2	28.9
54	Conecuh	Alabama	52.7	47.4	722584.9	8.2	0.6	1.9	1.6	21.8	30.2
55	Ouachita	Arkansas	52.6	48.4	731127.9	7.9	0.5	1.5	1.2	22.0	30.2
56	Barren	Kentucky	52.7	45.4	701883.0	8.8	0.9	2.2	1.7	21.2	30.2
57	Polk	Georgia	52.7	42.2	729548.4	8.1	0.4	1.5	1.2	22.0	30.3
58	Humphreys	Tennessee	52.7	45.8	709846.0	8.7	1.1	2.7	2.1	21.5	30.4
59	Winn	Louisiana	52.7	51.6	844866.4	4.7	0.0	0.1	0.1	25.4	30.4
60	Clark	Arkansas	52.6	51.1	719672.6	9.0	0.0	0.1	0.0	21.6	30.8
61	Stokes	North Carolina	52.7	51.2	712517.6	9.8	0.0	0.0	0.0	21.4	31.5
62	Rutherford	North Carolina	52.7	43.2	762679.6	8.5	0.5	1.4	1.1	23.0	31.7
63	Oconee	South Carolina	51.5	37.9	726546.7	9.8	0.1	0.4	0.3	21.8	31.9
64	Franklin	North Carolina	52.7	50.0	755019.6	9.7	0.1	0.2	0.2	22.7	32.7
65	Baldwin	Georgia	48.3	40.0	881502.6	8.5	0.0	0.0	0.0	26.4	35.3
66	Bamberg	South Carolina	52.5	50.3	846995.4	10.2	0.0	0.1	0.0	25.4	36.0
67	West Baton Rouge	Louisiana	52.7	44.1	804177.3	12.1	0.0	0.1	0.1	24.1	36.5
68	Marion	Georgia	48.7	40.1	903124.3	9.2	0.1	0.3	0.3	27.1	36.6

Table 15. Total annual woody biomass feedstock cost at $50% available mill wastes in the Southeast

Site Number	County	State	Unit Cost	Average Cost	Total Residues	Total Transportation Cost	Total Stumpage Cost	Total Chipping Cost	Other[11] Costs	Total residue Cost	Total feedstock Cost
			$/dry ton		Dry ton	Million dollars					
1	Brantley	Georgia	52.7	45.3	709238.9	6.2	0.8	3.1	2.5	21.5	27.9
2	Winn	Louisiana	52.7	45.9	725835.9	5.8	1.4	4.8	4.0	22.1	28.0
3	Bulloch	Georgia	52.7	44.8	716089.7	6.6	1.1	4.3	3.4	21.8	28.5
4	Wilkes	North Carolina	52.7	45.0	707209.3	7.2	0.9	2.4	2.0	21.4	28.8
5	Marion	Mississippi	52.7	45.3	703467.3	7.5	1.5	5.4	4.3	21.5	29.1
6	Williamsburg	South Carolina	52.7	45.3	701573.0	7.7	0.6	2.3	1.9	21.2	29.1
7	Cook	Georgia	52.7	45.6	709080.8	7.5	1.3	4.3	3.5	21.6	29.2
8	Jeff Davis	Georgia	52.7	45.6	720334.7	7.2	0.2	0.9	0.7	21.7	29.1
9	Glascock	Georgia	52.7	44.5	704182.4	7.4	1.3	5.3	4.1	21.5	29.0
10	Bamberg	South Carolina	52.7	43.7	715987.6	7.0	0.6	2.3	1.7	21.6	28.9
11	Jones	Georgia	52.7	45.6	702403.4	7.7	0.8	3.1	2.4	21.3	29.1
12	Chambers	Alabama	52.7	44.8	707328.3	7.5	1.2	5.1	4.1	21.6	29.2
13	Washington	Alabama	52.7	45.4	715473.7	7.5	0.8	2.6	2.0	21.6	29.3
14	Columbia	Arkansas	52.7	45.5	716290.7	7.3	1.4	5.1	4.1	21.8	29.3
15	Clark	Arkansas	52.7	44.8	700935.6	7.4	1.3	4.6	3.7	21.3	28.9
16	Montgomery	North Carolina	52.7	45.9	700618.3	7.9	1.7	5.4	4.2	21.4	29.4
17	Chatham	North Carolina	52.7	47.7	703142.2	7.9	1.1	3.1	2.4	21.3	29.4
18	Chesterfield	South Carolina	52.7	45.2	711214.1	7.7	0.8	2.9	2.2	21.5	29.5
19	Clark	Arkansas	49.9	40.9	726102.7	7.5	0.0	0.0	0.0	21.8	29.5
20	Columbia	Florida	52.7	44.3	712098.2	7.9	0.7	2.9	2.4	21.6	29.7
21	McCormick	South Carolina	52.7	46.6	727818.3	7.6	0.3	1.6	1.2	21.9	29.7
22	Jackson	Florida	52.7	44.9	702709.9	8.7	1.1	3.8	3.2	21.3	30.2

[11] Includes cost of mill waste

Table 15. Continued

Site Number	County	State	Unit Cost	Average Cost	Total Residues	Total Transportation Cost	Total Stumpage Cost	Total Chipping Cost	Other Costs	Total residue Cost	Total feedstock Cost
			$/dry ton		Dry ton	Million dollars					
23	Marion	Georgia	52.5	42.2	720194.2	8.3	0.6	2.1	1.6	21.7	30.3
24	Tuscaloosa	Alabama	52.7	45.6	702671.7	8.7	2.1	7.9	6.0	21.6	30.4
25	Pickens	Alabama	52.7	50.4	719439.0	7.8	0.3	1.0	0.9	21.7	29.7
26	Choctaw	Mississippi	52.7	45.2	707593.2	7.9	2.0	6.9	5.6	21.7	29.7
27	Floyd	Georgia	52.7	45.6	701121.0	9.0	1.6	5.0	3.8	21.4	30.5
28	Halifax	North Carolina	52.7	45.6	700106.0	9.0	1.6	5.6	4.4	21.4	30.5
29	Louisa	Virginia	52.7	45.4	705791.3	9.4	1.5	4.6	3.5	21.5	31.0
30	Copiah	Mississippi	52.7	46.0	720797.6	9.1	0.6	2.0	1.6	21.8	31.1
31	Humphreys	Tennessee	52.7	46.4	704685.7	9.6	1.6	4.1	3.2	21.4	31.2
32	Amelia	Virginia	52.7	46.5	721623.1	9.9	1.3	4.0	3.1	21.9	32.0
33	Hardin	Tennessee	52.7	45.3	719187.0	10.5	1.2	3.8	3.0	21.8	32.5
34	Laurens	South Carolina	52.7	46.5	703280.8	11.1	0.5	1.9	1.5	21.2	32.6

Table 16. Total annual woody biomass feedstock cost at 10% available mill wastes in the Southeast

Site Number	County	State	Unit Cost	Average Cost	Total Residues	Total Transportation Cost	Total Stumpage Cost	Total Chipping Cost	Other[12] Costs	Total residue Cost	Total feedstock Cost
			$/dry ton		Dry ton	Million dollars					
1	Tuscaloosa	Alabama	52.7	45.6	701555	9.1	2.1	7.9	6.0	21.6	30.8
2	Warren	Georgia	52.7	45.6	710047	9.2	1.8	7.1	5.6	21.8	31.0
3	Dallas	Arkansas	52.7	45.8	703241	9.5	1.9	6.8	5.5	21.6	31.1
4	Durham	North Carolina	52.7	45.3	703327	9.6	2.8	8.1	6.4	21.7	31.4
5	Amelia	Virginia	52.7	45.5	700074	10.2	3.2	10.4	8.1	21.7	31.9
6	Loudoun	Virginia	52.7	44.1	132747	1.9	0.8	1.8	1.3	4.1	6.0

[12] Includes cost of mill wastes

Table 17. Estimated economic impact of biofuels activity in the Southeast

Outputs	Feedstock	Conversion to Biofuels						
	Chips	Credits	Investment	Labor	Operations	RIN	Transportation	**Total**
					In millions			
Output, $								
Direct	37.09	57.65	9261.37	39.91	1455.21	1701.69	278.92	12,831.84
Indirect	8.83	0.00	3612.61	0.00	402.18	0.00	83.49	4,107.11
Induced	14.44	37.62	3076.42	26.05	485.02	1110.52	109.68	4,859.75
Total	60.36	95.28	15950.40	65.96	2342.41	2812.21	472.09	21,798.70
Employment[13]								
Direct	0.0004	0.0000	0.0535	0.0000	0.0093	0.0000	0.0035	0.0667
Indirect	0.0001	0.0000	0.0250	0.0000	0.0027	0.0000	0.0006	0.0283
Induced	0.0001	0.0003	0.0233	0.0002	0.0037	0.0085	0.0008	0.0369
Total	0.0006	0.0003	0.1018	0.0002	0.0157	0.0085	0.0049	0.1320
Value Added, $								
Direct	24.21	57.65	3800.39	39.91	740.75	1701.69	172.31	6,536.91
Indirect	4.96	0.00	1825.39	0.00	212.78	0.00	46.79	2,089.92
Induced	8.12	21.15	1735.74	14.64	273.17	624.14	61.77	2,738.74
Total	37.29	78.80	7361.52	54.55	1226.70	2325.84	280.87	11,365.57
Labor Income, $								
Direct	19.14	57.65	3333.09	39.91	599.51	1701.69	138.20	5,889.19
Indirect	2.54	0.00	1132.09	0.00	122.29	0.00	25.05	1,281.99
Induced	4.43	11.52	954.91	7.97	149.54	339.92	33.71	1,502.00
Total	26.11	69.17	5420.09	47.88	871.34	2041.62	196.97	8,673.18

[13] Number of Jobs created

Table 18. Estimated regional economic impact of Biofuel activity in the Southeast

Bureau of Economic Analysis Region	Total Industry Output	Total Employment	Total Value Added	Total Labor Income
	Million, $	Million Jobs	Million, $	Million, $
1	529.94	0.0032	264.44	208.68
2	582.14	0.0035	297.53	211.15
7	543.15	0.0031	288.12	209.30
18	560.33	0.0035	291.14	227.05
20	601.47	0.0034	328.44	253.93
36	568.96	0.0035	297.98	228.47
42	**884.17**	**0.0049**	**489.68**	**360.79**
45	844.39	0.0047	462.31	351.70
55	673.15	0.0041	360.98	277.92
63	466.13	0.0029	243.74	196.59
65	505.26	0.0032	250.35	199.51
73	569.80	0.0037	290.80	223.23
83	472.33	0.0032	223.86	174.04
84	799.39	0.0047	438.08	339.61
85	469.56	0.0030	239.53	178.91
86	516.60	0.0029	292.98	225.08
93	486.36	0.0031	231.94	177.08
95	636.40	0.0041	329.69	244.81
99	605.25	0.0038	318.04	229.82
109	789.31	0.0044	435.10	322.87
110	437.22	0.0022	255.89	219.00
119	660.49	0.0040	337.39	258.67
124	438.64	0.0030	215.61	173.11
131	773.84	0.0045	427.92	329.96
132	449.00	0.0028	234.54	188.12
134	635.03	0.0041	292.00	235.46
141	476.98	0.0031	233.84	183.82
143	598.82	0.0037	299.36	210.81
150	509.05	0.0033	254.84	194.40
154	532.64	0.0034	274.52	209.48
155	692.81	0.0042	357.70	271.99
157	649.74	0.0040	339.24	244.51
167	529.45	0.0031	277.05	217.84
170	754.95	0.0044	388.75	297.04
177	461.56	0.0027	248.45	183.07
178	539.95	0.0033	266.72	188.45
179	554.43	0.0034	287.01	226.91

Table 19. Bureau of Economic Analysis, Region #42: Top 5 sectors impacted the Biofuels facility investment in the Southeast

Industry	Employment	Labor Income	Value Added	Industry Output
	Number of jobs created	in thousand, $		
Construction of other new nonresidential structures	834.6	59,197.7	71,840.8	161,537.9
Nondepository credit intermediation and related activities	443.4	37,420.8	39,620.2	79,794.5
Insurance carriers	165.6	12,882.8	22,817.8	51,335.6
Architectural, engineering, and related services	309.6	26,123.8	23,464.6	42,880.5
Insurance agencies, brokerages, and related activities	151.4	10,574.1	13,281.1	27,641.6

Table 20. Bureau of Economic Analysis Region #42: Top 5 sectors impacted the Biofuels feedstock (chips) utilization in the Southeast

Industry	Employment	Labor Income	Value Added	Industry Output
	Number of Jobs created	in thousand, $		
Commercial and industrial machinery and equipment repair and maintenance	4.1	336.5	389.9	566.9
Retail - Gasoline stores	5.9	226.2	313.0	464.9
Real estate	0.6	17.7	70.0	95.0
Owner-occupied dwellings	0.0	0.0	47.8	67.7
Wholesale trade	0.2	19.0	36.5	51.1

Table 21. Traffic flows and transportation emissions of three selected biorefinery sites in the Southeast

Site Number	Total truck load	Total truck Volume	Total Nitrogen oxide (NOx)	Total Carbon Dioxide (CO2)	Total Particulate Matter		Total Truck distance traveled
					PM10	PM2.5	
	in millions		in tons				million miles
1	4.1	8.2	31.5	3,277.2	2.0	1.5	1.8
5	3.2	6.4	28	3,003.5	1.9	1.4	1.6
68	4.9	9.7	44	4,437	2.9	2.1	2.5

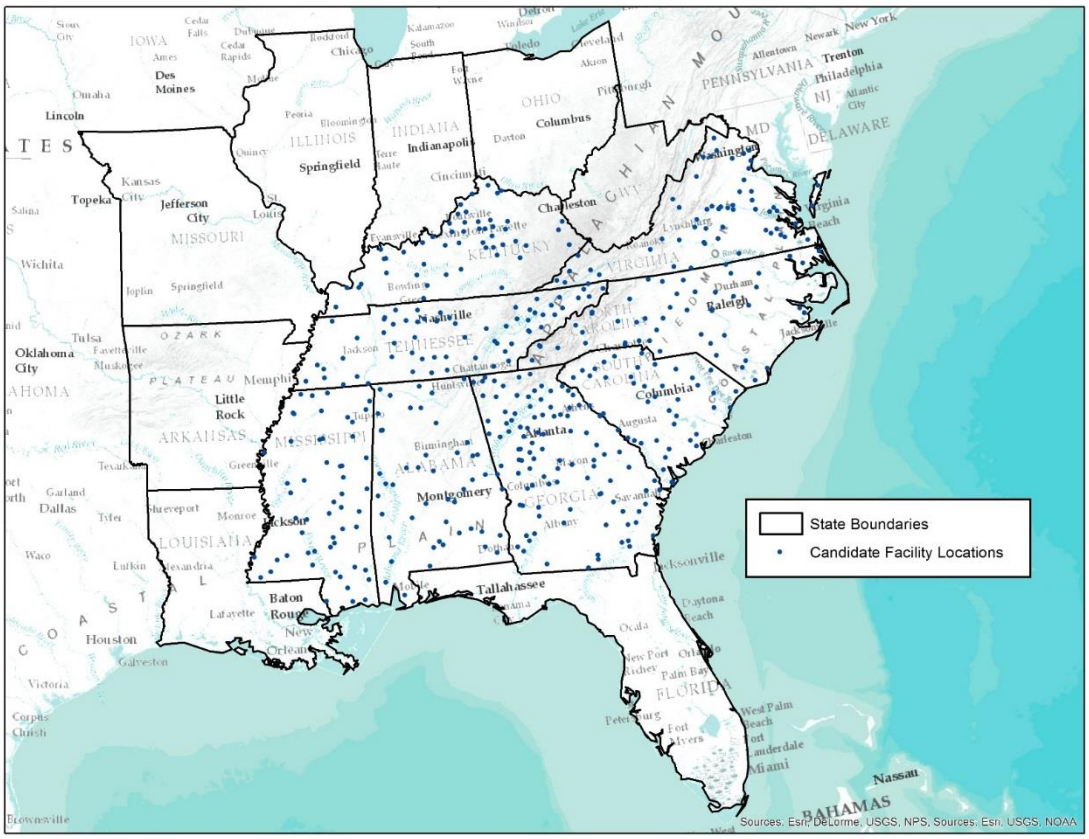

Figure 13. Industrial Park locations (candidate facilities) in the South

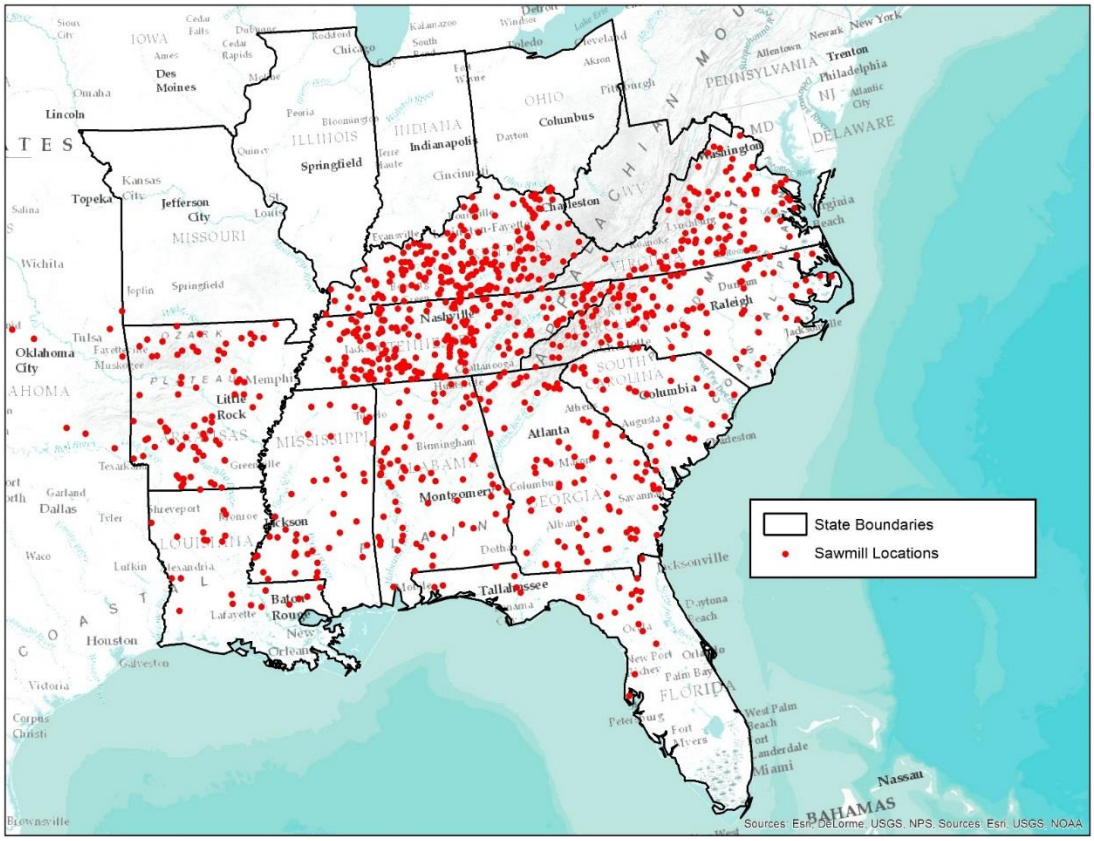

Figure 14. Locations of all sawmill facilities in the Southeast

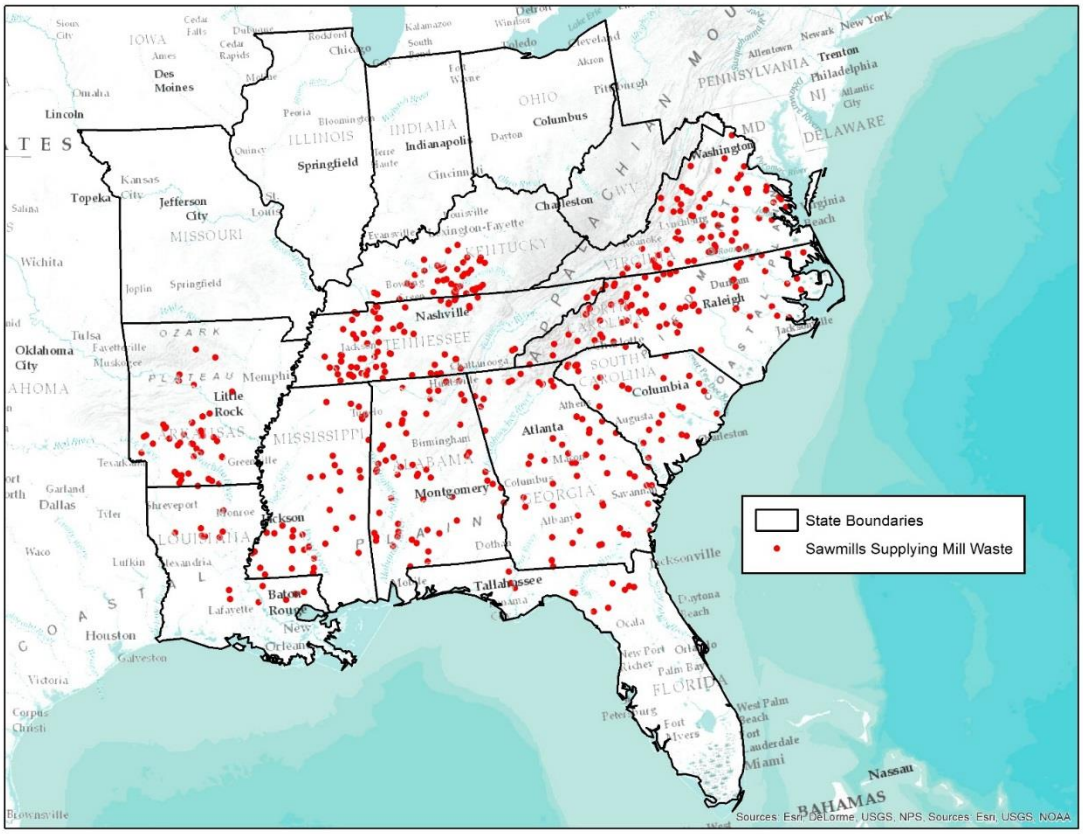

Figure 15. Location of potential sawmills supplying 100% mill wastes in the Southeast

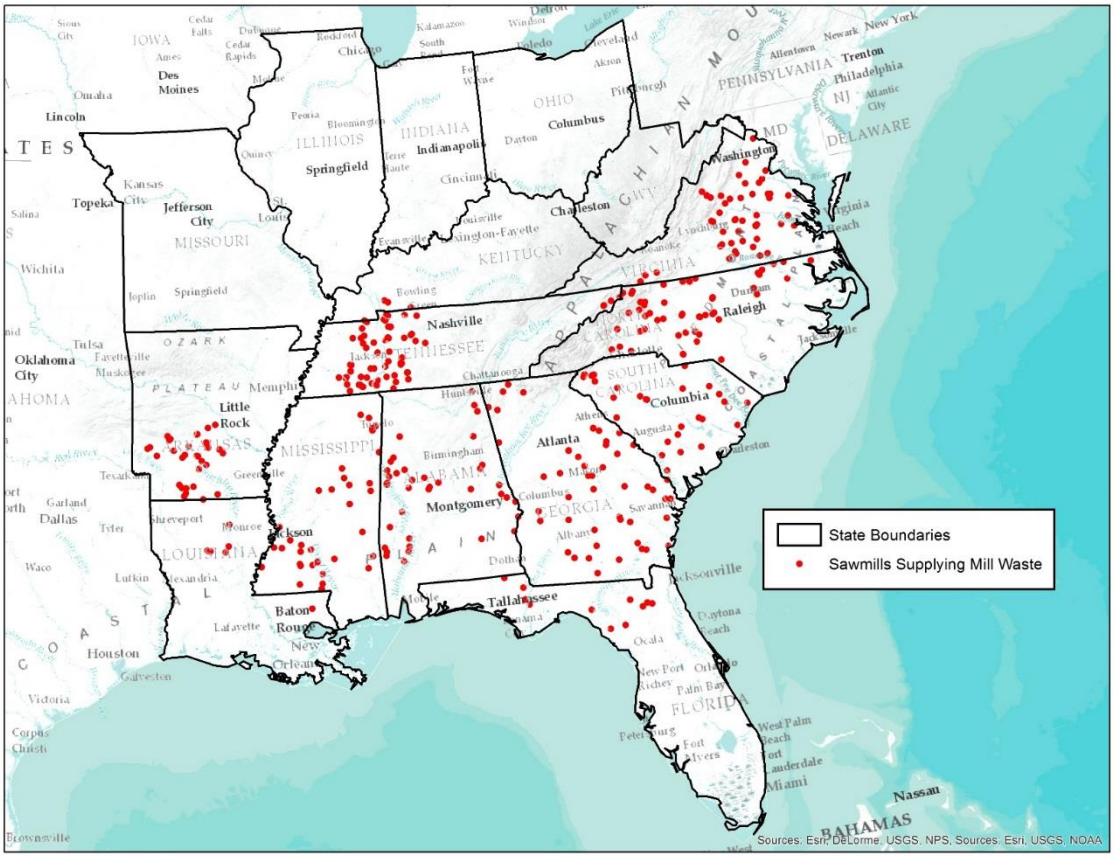

Figure 16. Location of potential sawmills supplying 50% mill wastes in the Southeast

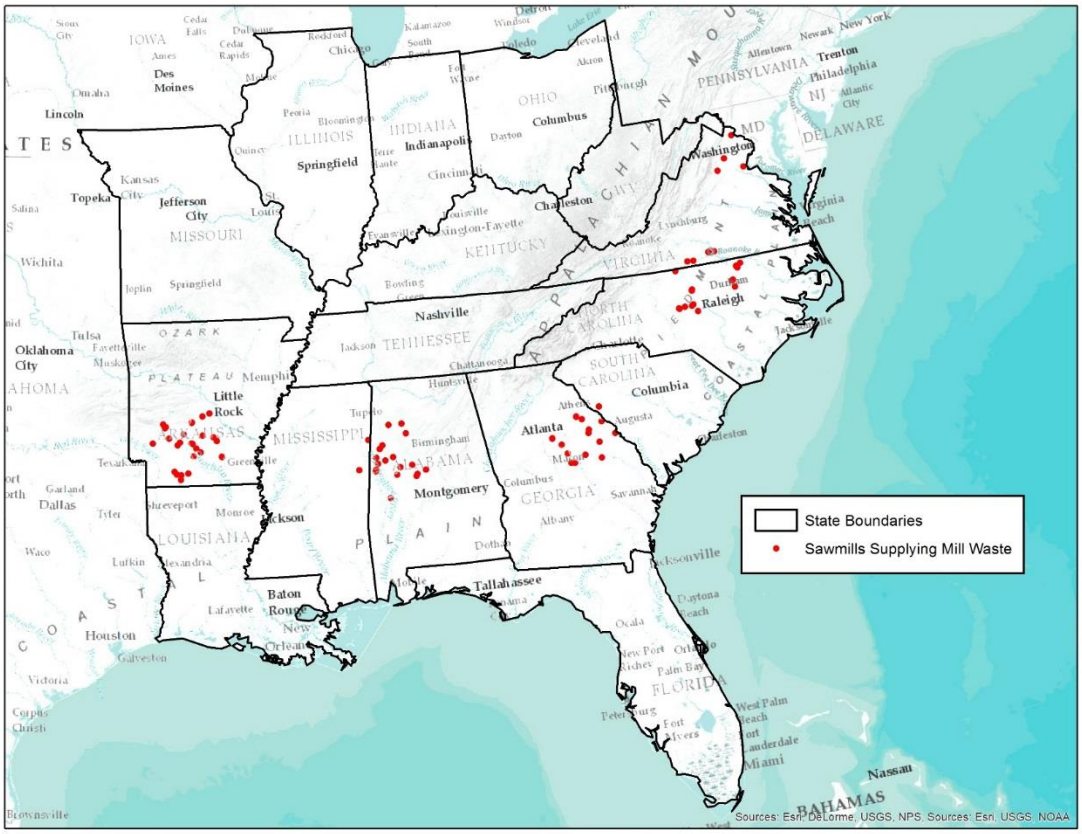

Figure 17. Location of potential sawmills supplying 10% of mill wastes in the Southeast

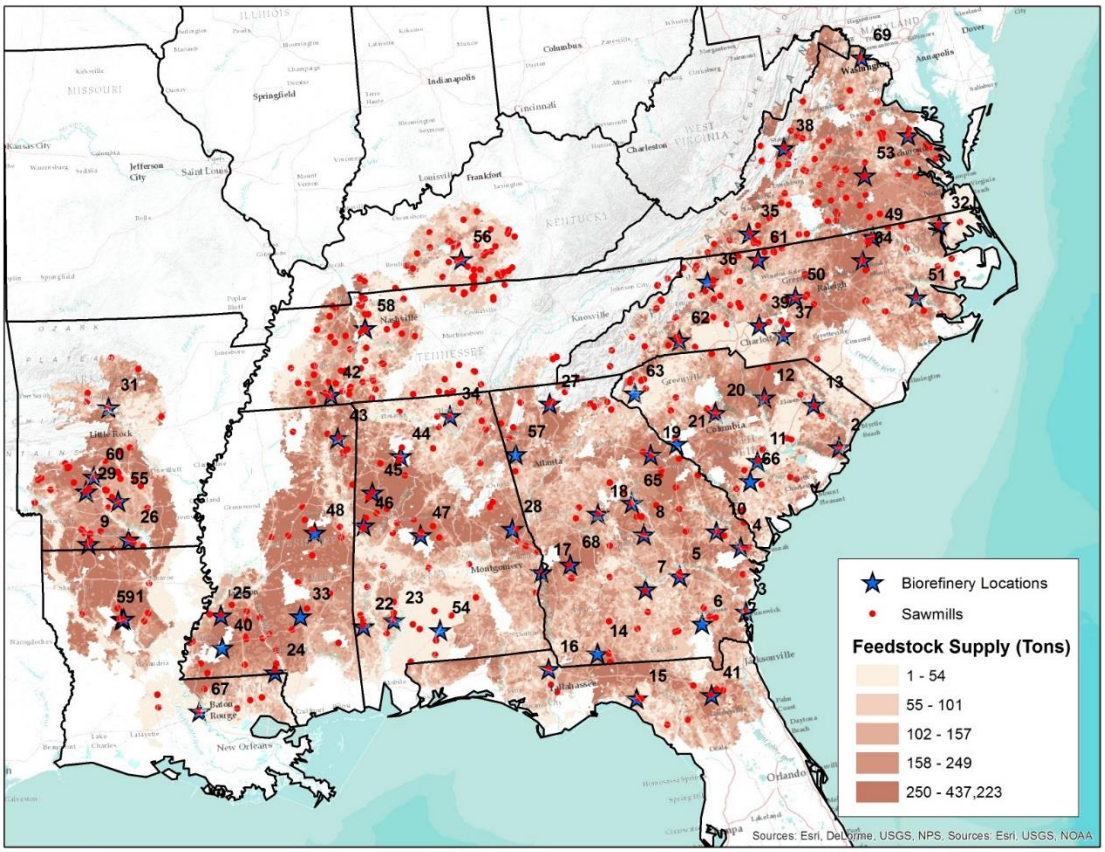

Figure 18. Optimal site of biorefineries and feedstock supply (100% mill waste) in a 5-square mile area hexagon in the Southeast

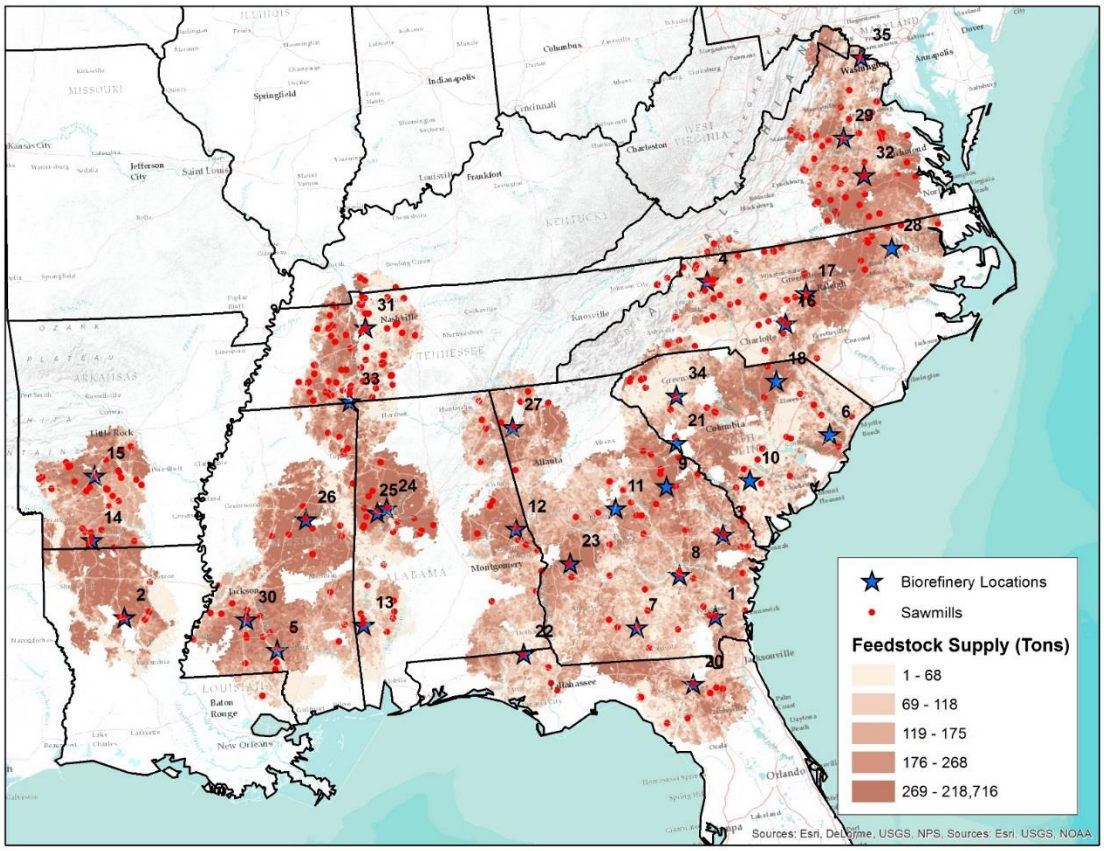

Figure 19. Optimal site of biorefineries and feedstock supply (50% mill waste) in a 5-square mile area in the Southeast

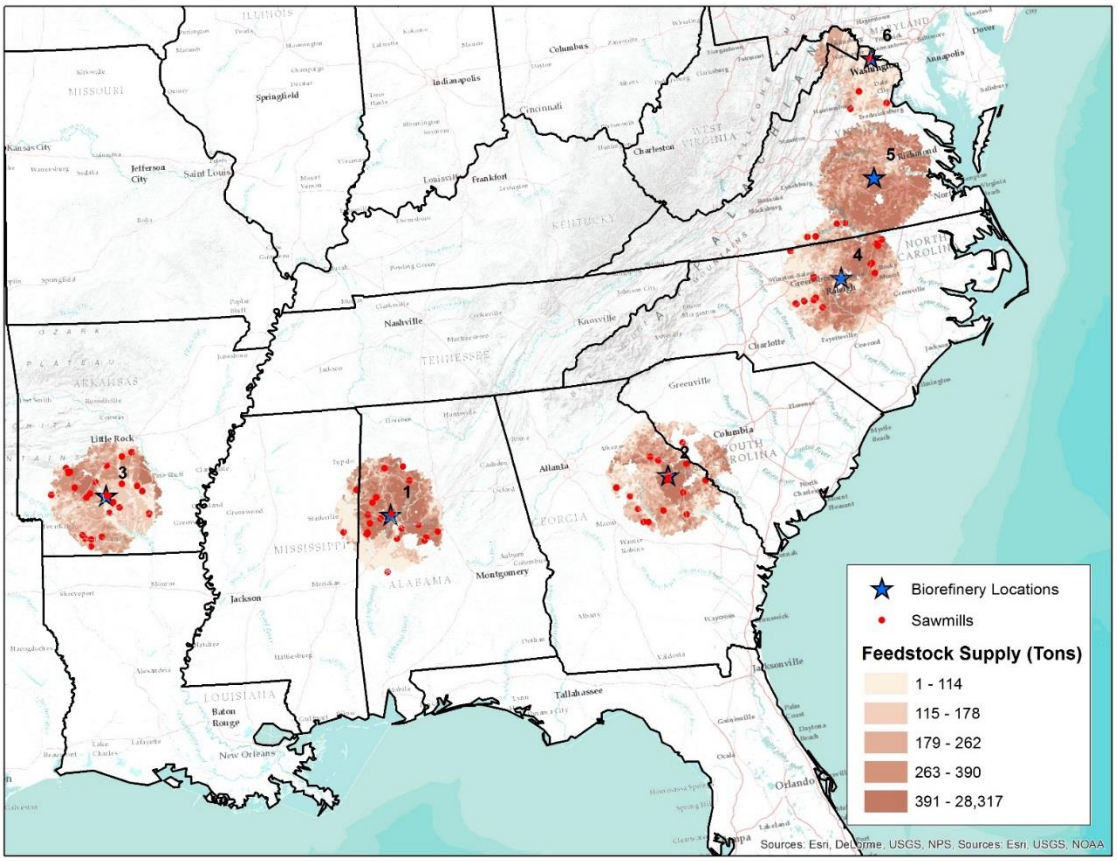

Figure 20. Optimal sites of biorefineries and feedstock supply (10% mill waste) in a 5-square mile area in the Southeast

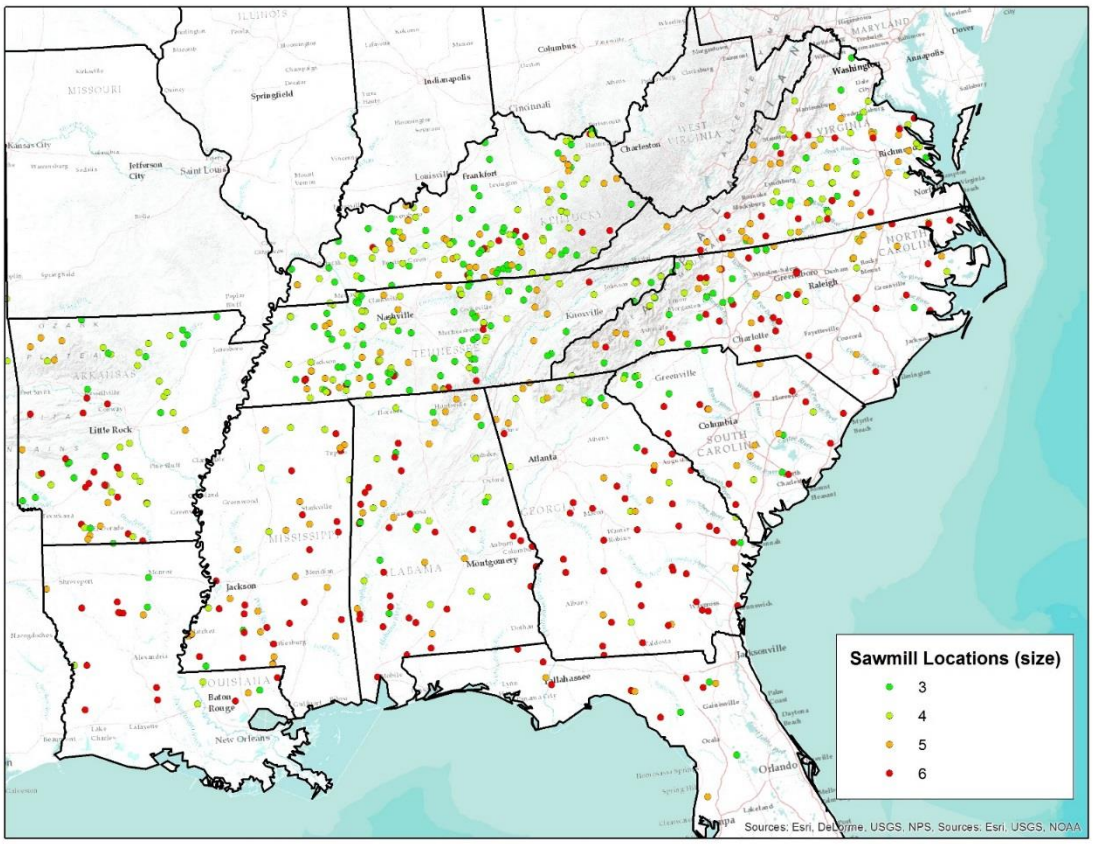

Figure 21. Locations of sawmills with capacity size 3-6 mbf in the Southeast

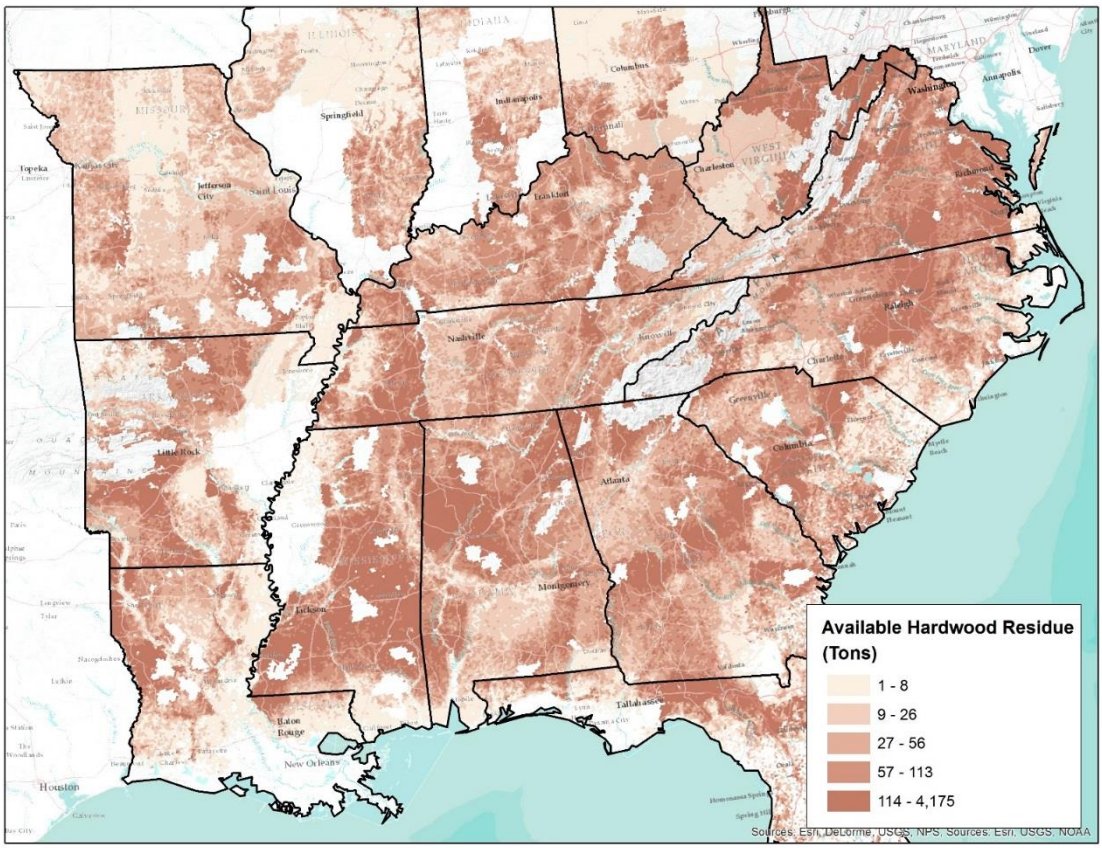

Figure 22. Location of available hardwood logging residues in the 5-square mile area in the Southeast

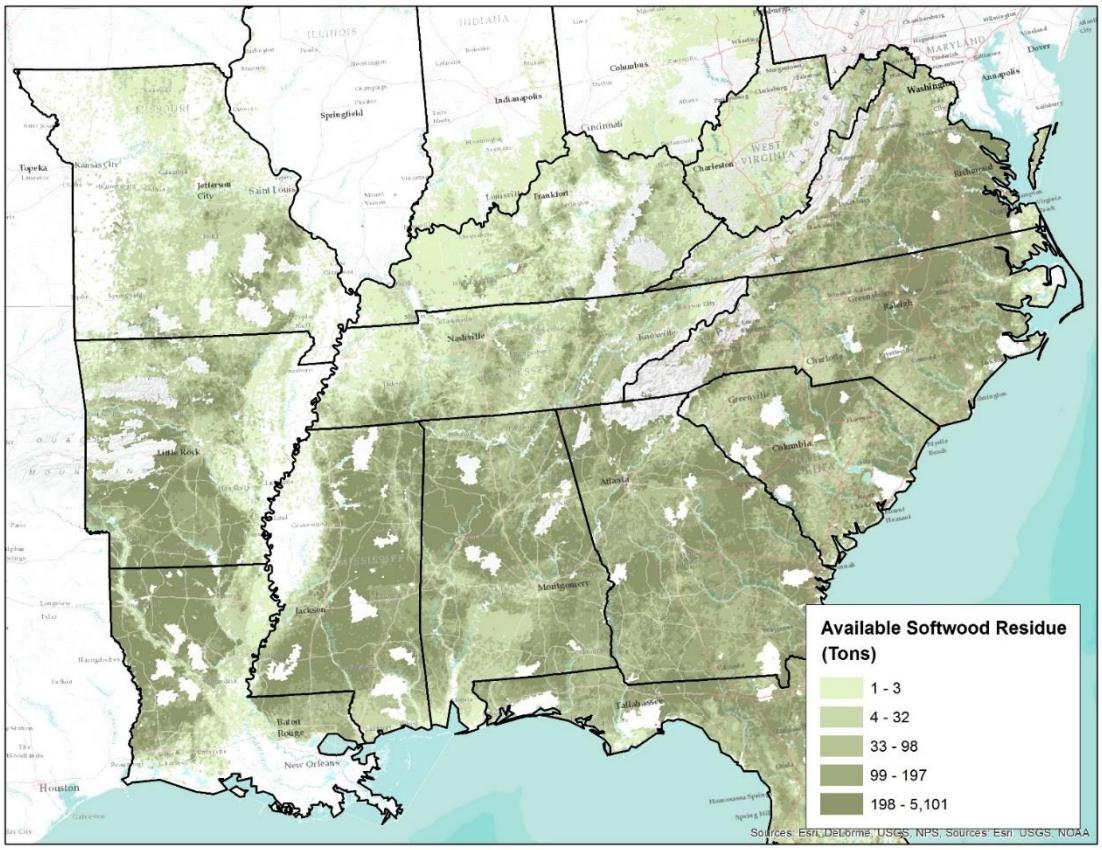

Figure 23. Location of available softwood logging residues in the 5-square mile area in the Southeast

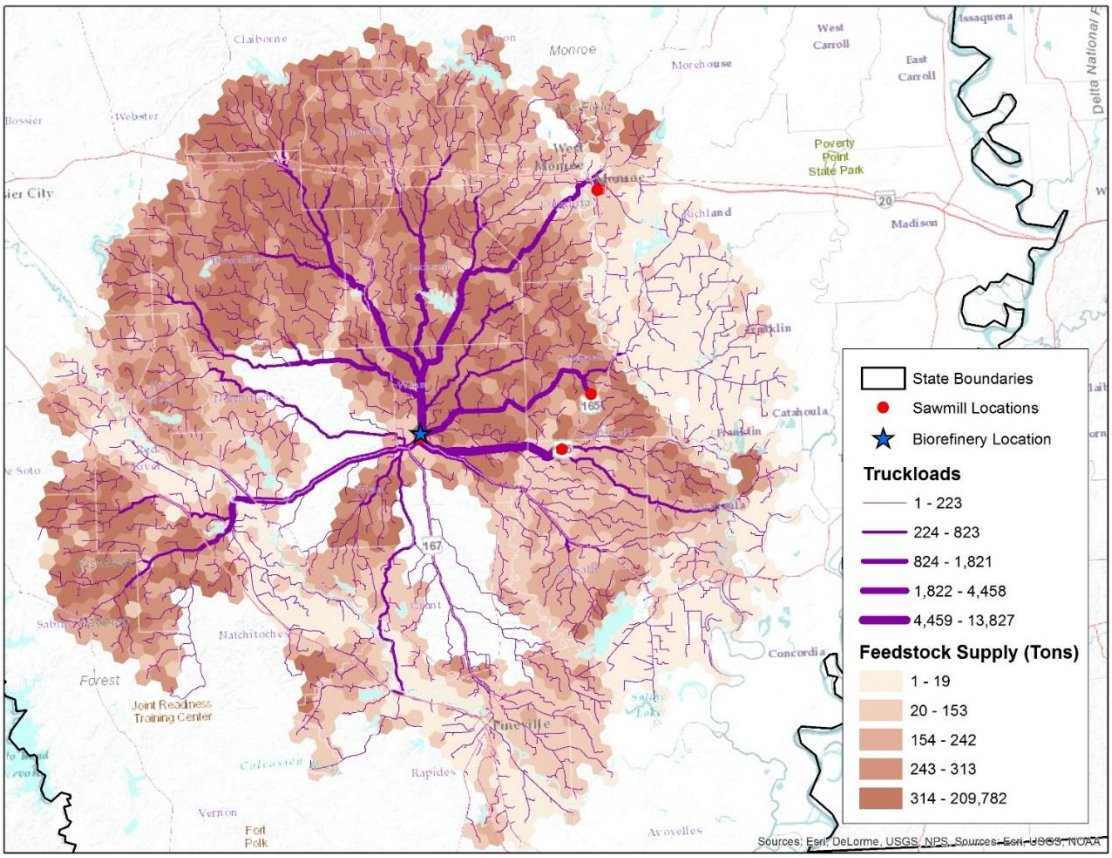

Figure 24. Sited Bioefinery #1 (Winn, Louisiana) traffic flows and feedstock sources in the Southeast

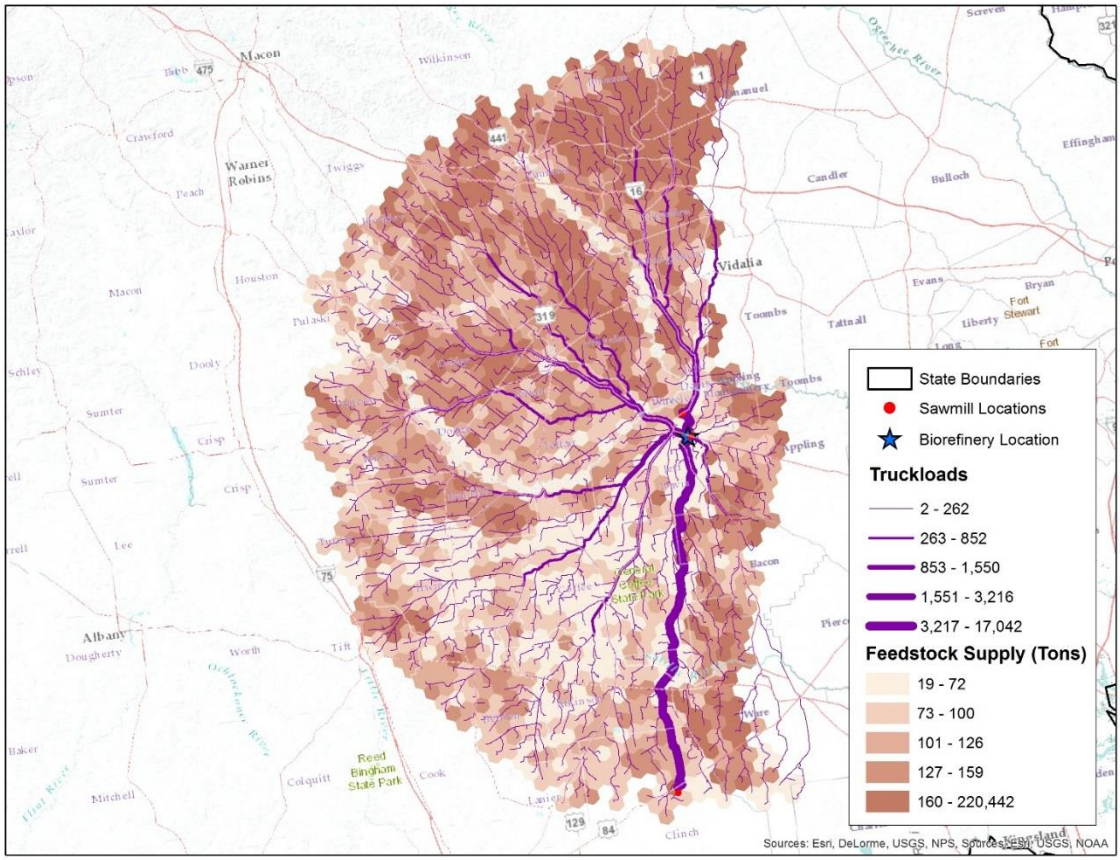

Figure 25. Sited Bioefinery #5 (Jeff Davis, Georgia) traffic flows and feedstock sources in the Southeast

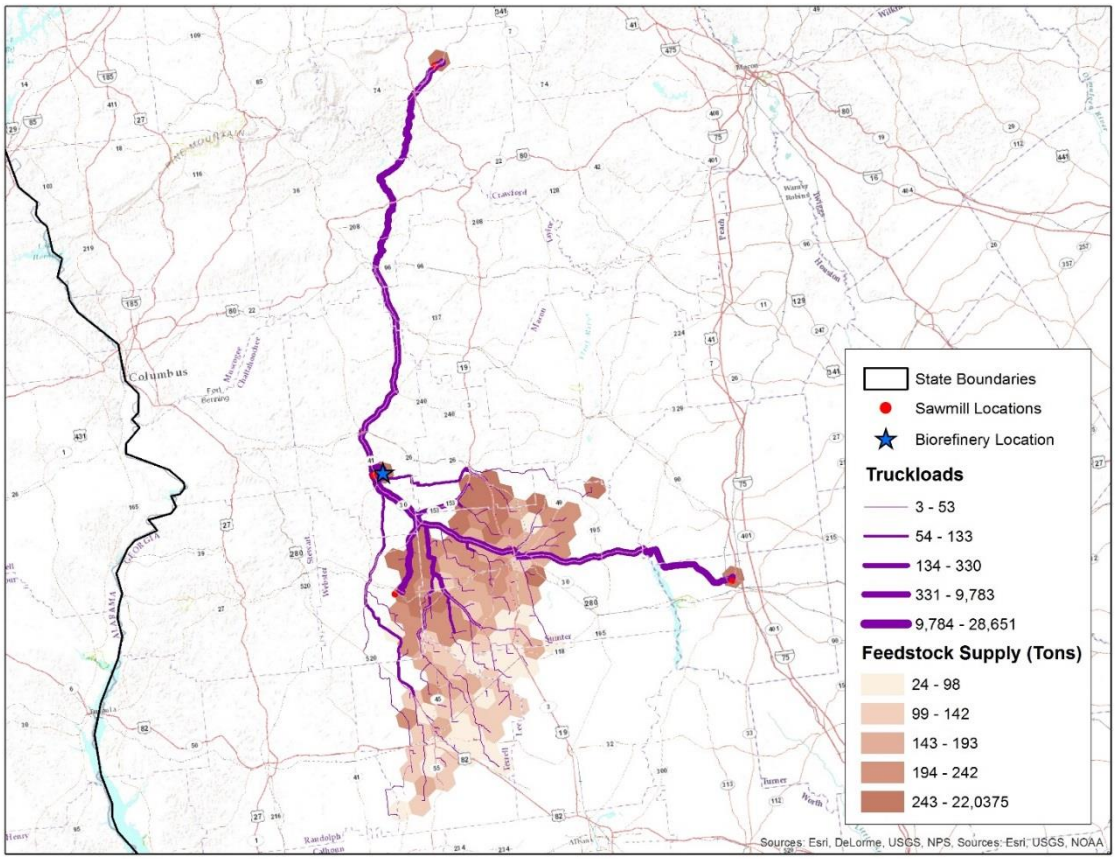

Figure 26. Sited Bioefinery #68 (Marion, Georgia) traffic flows and feedstock sources in the Southeast

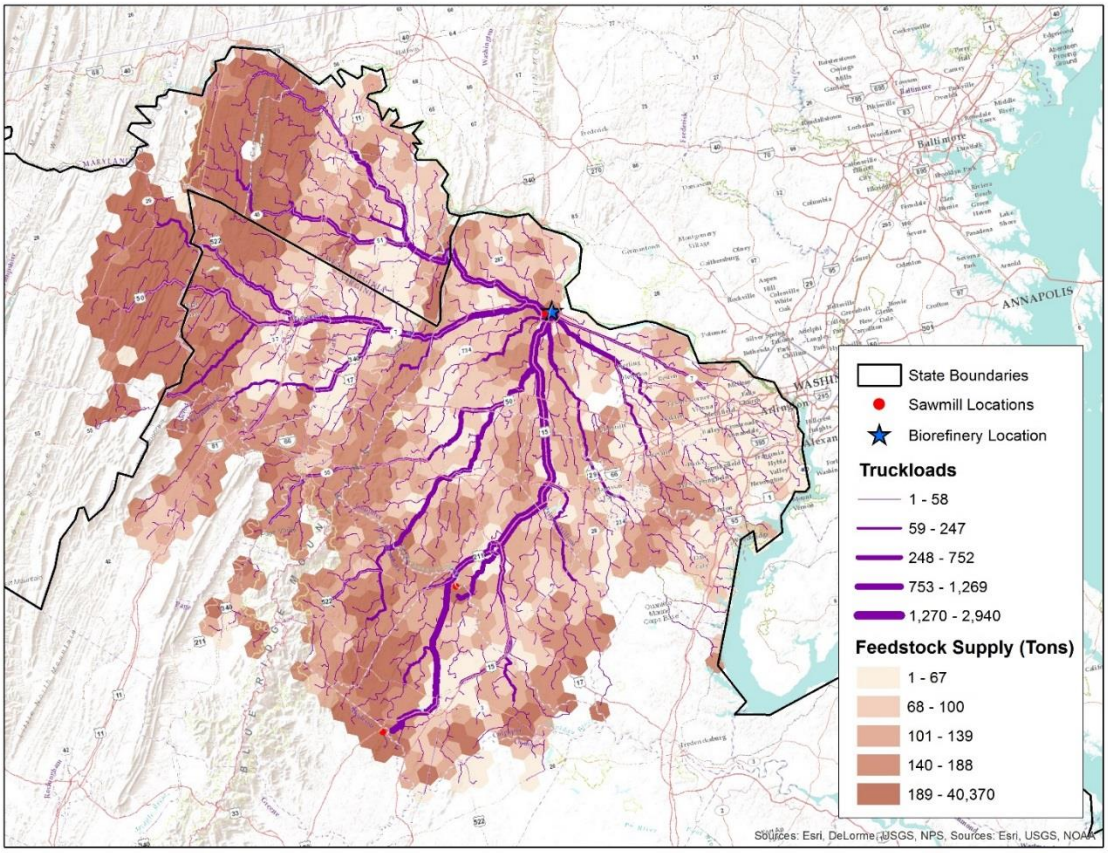

Figure 27. Sited Bioefinery #69 (Loudon, Virginia) traffic flows and feedstock sources in the Southeast

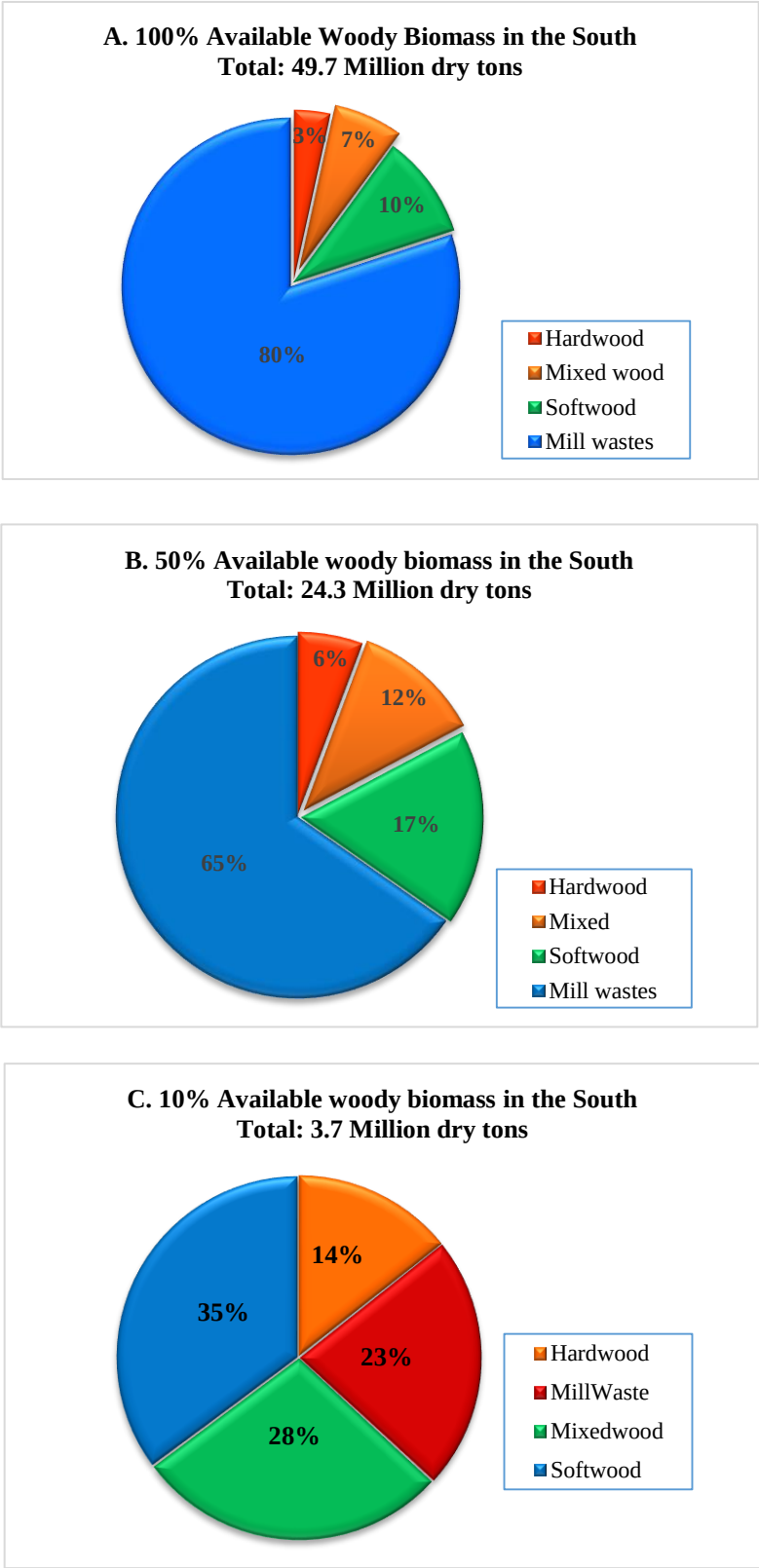

Figure 28. Available woody biomass feedstocks in the Southeast

Chapter V: Summary and Conclusions

In the U.S. where the economy is built largely on transportation systems, access to clean and low-cost transportation is vital and currently relies on fossil fuels. The use of renewable energy could lead to a more sustainable development and reduce supply vulnerability and price spikes. Forests are vast carbon sink, storing carbon as biomass. They are frontiers to minimize impacts of climate change. Forests also provide timber and non-timber values, wildlife habitat and refuge, recreation, food and income. Forest growth and development are vital to environmental sustainability.

The Energy Independence and Security Act of 2007 requires the expanded Renewable Fuel Standards program to increase the use of cellulosic biofuels. Under the program, the obligated parties are required to blend petroleum with biofuels. Woody biomass sources exist and are abundant. Harvesting logging residues and non-merchantable timber provide significant biomass to meet some of the bioenergy demand. Technologies have improved in efficiency of converting woody biomass to biofuels. Developing this sector has economic impact to the local economies. Despite the sizeable economic prospects, concerns over costs of harvesting, and procurement of biomass remain a challenge. Few investors are interested to pioneer investments due to technological risks. The siting of optimal biorefinery locations relative to biomass source and feedstock cost is challenging.

This dissertation focuses on the harvesting and utilization of woody biomass as a potential cellulosic feedstock for bioenergy. Chapter 2 examines the use of logging residues and whole-tree woody biomass as feedstocks to biofuel production. Essentially, it provides measures of the impact on the sustainability criterion on forest residues availability for bioenergy. The Forest Sustainable Economic and Analysis Model (ForSEAM), a linear cost minimization model

is used to simulate woody biomass supply curves over time to meet conventional timber and bioenergy demands subject to several constraints. Sustainability issues include a) building of temporary roads that may influence streams and water quality, soil erosion, wildlife habitat and refuge, b) restriction on timber harvest relative to growth rate. Thus cannot harvest more than the growth rather previously timber harvested acres are allowed to grow and regenerate until it become class 2, and c) cable yarding system harvesting in the North region was allowed in areas greater than 40% slope, but, no logging residues were collected. The woody biomass supply curve was simulated in two scenarios: a) ½-mile and 1-mile road harvest distance. At $40-$80 price per dry ton, the total available potential feedstock in the U.S. range from 21 million dry tons to 133 million dry tons in ½-mile and up to 254 million dry tons in the 1-mile road harvest distance from 2020 to 2040. Extending the modeling period from 2045 to 2055, at $80 per dry ton, the 1-mile distance biomass supply is approximately 120 million dry tons while the ½-mile road harvest distance has much lesser biomass supply. At prices below $40 per dry ton, most of the biomass comes from logging residues. The majority of the woody biomass originates on private timberlands located in the South. The available biomass declines over time because of the restrictions embedded in the model. For instance, timberlands are assumed to regenerate after the harvest, the annual growth is not projected to increase, and harvest is restricted to no more than 5% at the state level in any given year.

Chapter 3 provides estimates of the potential changes of southern timberlands over time and its ability to meet conventional timber products and bioenergy demand. The supply of biomass to meet conventional timber and bioenergy demand are estimated using ForSEAM. The model was modified to track the annual changes of existing timberland harvested and regenerated, and the remaining acres available for harvest. Two scenarios were examined over

time. Scenario 1 assumes that existing stand growth and acreages do not vary, and scenario 2 assumes that acreages, stand growth and regeneration vary over the modeling period. The annual changes in stand growth and existing timberlands were tracked using the updated ForSEAM transition matrix. This transition matrix contains data on tree species; class stands, and stand age by POLYSYS region. In addition, the analysis excluded acreages without yield information and those forestlands classified as reserved. Results show that supply of woody biomass range from 5 million to 90 million dry tons contingent to prices. At prices below $40 per dry ton, most biomass available are logging residues. At $70 per dry ton, 90 million dry tons are available in 2020 and 55 million dry tons in 2055 mostly from whole-tree biomass. From 2020 to 2055, scenario 2 has more potential woody biomass supply than scenario 1. However, the availability of biomass decline over time.

Chapter 4 integrates the BioFLAME and IMPLAN models to simulate available cheapest feedstock, and site economically feasible biorefinery location and to estimate the economic impact of biofuel activity in the southeast, respectively. BioFLAME was modified to allow the model to utilize logging residues and mill wastes. The supply of logging residues was simulated using ForSEAM and aggregated at POLYSYS level by species. The supply of mill wastes was estimated using simple regression analysis. The assumed mill wastes availability was varied depending on the scenario. The forestland cover and available logging residue supply in southeastern region were downscaled into equal hexagons consisting of a 5-square mile area. A 30-meter pixel level, high-resolution cropland data layer was used to assess the location of the forest cover in the Southeast. Both the forestland acres and the ForSEAM estimated logging residues available at the POLYSYS region were broken down and assigned for each hexagon. The amount of logging residues located within the boundary were linked through each hexagon.

The available tonnage of logging residues for each hexagon was calculated. Considering the magnitude of the real world industrial parks present in the region, a number of industrial parks were selected as potential candidate nodes (centroids of spatial hexagons). In addition to the industrial park candidate facility locations, medium to large sized sawmills were added, increasing the total number of candidate facilities across the Southeast. The feedstock least cost analysis was constructed. The model sites potential biorefineries based on the lowest feedstock procurement cost. For multiple sited biorefineries, each facility is sited in sequence so that the lowest feedstock cost is labeled unavailable forcing the next biorefinery to look for feedstock elsewhere. A total of 68-sited biorefineries with an annual feedstock demand of 50 million dry tons. The estimated total feedstock cost is $2 billion with direct biomass cost accounts 76% and 24% for transportation.

The biorefineries were ranked based on delivered feedstock costs. Assuming 100% mill waste availability, the rank #1 biorefinery is located in Winn, Louisiana with a feedstock cost of $28 million and rank #68 is located in Marion, Georgia with cost of $37 million. Moreover, reducing the mill waste available to 50% and 10%, the number of sited facilities decline to 34 and 5, and the rank #1 facilities shift to Brantley, Georgia, and Tuscaloosa, Alabama, respectively. The traffic flows and transportation emissions are affected by the slope of the road, distance and location of biorefineries to biomass source. For purposes of comparison, three selected potential sites were compared to assess the variations in traffic flows and emissions: Site #1 (Winn, Louisiana), site #5 (Jeff Davis, Georgia) and #68 (Marion, Georgia). The truck volume and traffic flows from sawmills to the sited biorefineries #1, #5 and #68 are denser than logging residues indicating that mill wastes are important source of biomass for these biorefineries. Site #1 requires about 4 million truckloads every year with a total annual emission

of 32 tons of NO_x and 3,277 tons of CO_2. The highest transportation emission is sited facility #68. The total emission is roughly 44 tons of NO_x and 4,437 tons of CO_2 per year.

Biofuels activity has sizeable economic impacts in the region. The estimated total industry output is $22 billion with a direct output value of $13 billion generating 132,000 jobs in the local economy. Indirectly, the biofuel industry brings about $4.1 billion to input suppliers and other backward industry linkages. At the regional level, the Bureau of Economic Analysis region #42 (Texas and some part of Oklahoma) has largest economic impact amounting to $888.17 million. The estimated value addition is $489.68 million. The top sector with highest economic impact is the construction of other new nonresidential structures with $161.5 million.

With an increased demand placed on U.S. forestlands, the forests become young and require time to regenerate and the mature forest area decreases. Findings of the study could assist the government in formulating policy actions toward sustainable timber harvesting and utilization of woody biomass feedstock by providing incentives on the use of improved tree genomics to increase productivity and hasten stand age maturity to allow more frequent timberland harvest. A policy action can also be directed on training specialists on biomass feedstock utilization and educating timberland owners on the importance of forest woody biomass in the development of bioenergy program. Furthermore, the result of the study can also be an important guide for the government to create policy actions toward the development of biofuel markets, and elicit biorefinery investments through the provision of monetary incentives and insure biorefineries of continuous biomass feedstock supply at competitive prices.

Vita

Gerry Solano Avila was born in Cebu City, Philippines on January 10, 1970. He obtained his Bachelor of Science in Agriculture major in Agricultural Economics in 1991 from the Visayas State College of Agriculture now known as the Visayas State University in Leyte, Philippines. After finishing college, he worked as a Science Research Assistant at the Farm and Resource Management Institute prior to joining the Department of Agriculture-Regional Field Office VII, Cebu City, Philippines. In 2004, he entered graduate school at the Department of Agricultural and Resource Economics, University of Tennessee-Knoxville. He received his Master of Science in Agricultural Economics in 2006. He was then a recipient of the 2004-2006 Fulbright Philippine Agriculture Scholarship Program. In 2017, he was awarded PhD in Natural Resources.