ABSTRACT

CALDWELL, WILLIAM JAMES. Forest Carbon Effects of Biomass Feedstock Species Selection in Southeastern U.S. (Under the Direction of Dr. Robert C. Abt)

The recent and rapid expansion of sourcing wood pellets for European Union (EU) bioenergy demand from southeastern U.S. forests is affecting short and midrange forest carbon stocking. Woody biomass feedstocks in the region are primarily either sourced from softwood or hardwood species, but the difference in forest carbon effects from the feedstock selection due to species has not been thoroughly examined. This study aims to estimate and explain the differences in forest carbon over a 30 year period between different biomass species selection feedstocks and a biomass free baseline through modeled scenarios that incorporate land-use change and forest markets. Results showed that forest carbon increased with dominant-softwood use compared to the baseline by as much as 2.15% on average over the entire period of analysis, while hardwood-dominant use decreased forest carbon levels by as much as 1.7% below the baseline on average. Softwood-dominant biomass use led to forest carbon and forestland acreage increases on pine plantations, in addition to slight gains in hardwood forests that outpaced losses in natural pine forests. Dominant hardwood biomass selection still increased forestland acreage on a whole due to a slight increase in softwood biomass demand as well, but also led to forest carbon loses in hardwood forests and natural pine forests. The differences in feedstock species selection carbon outcomes are due to market effects on land use change dynamics in the southeastern United States.

© Copyright 2017 William James Caldwell

All Rights Reserved

Forest Carbon Effects of Biomass Feedstock Species Selection in Southeastern U.S.

by
William James Caldwell

A thesis submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the Degree of
Master of Science

Natural Resources

Raleigh, North Carolina
2017

APPROVED BY:

Dr. Fredrick W. Cubbage	Dr. Dennis W. Hazel

Dr. Robert C. Abt
Chair of Advisory Committee

BIOGRAPHY

Will Caldwell is native to the southeastern United States, growing up in South Carolina and North Carolina. He started his Bachelors of Science degree in Natural Resources: Policy and Administration at North Carolina State in 2008, graduating summa cum laude in 2012. During this time he was awarded academic funding through the James L. Goodwin Academic Scholarship from 2010-2012. During his undergraduate career, the author interned and worked part-time at the Triangle Land Conservancy, as well as working in Department of Horticulture at North Carolina State University. In addition to his studies in Raleigh, Will took courses in forestry and sustainable natural resource use in Los Ríos Region of Chile as well as the U.S. Pacific Northwest.

In 2012, Will started as graduate student and graduate research assistant at North Carolina State University in Natural Resources: Economics and Management under the direction of Dr. Robert C. Abt. His studies and research were funded by the North Carolina State University-based Southern Forest Resource Assessment Consortium (SOFAC). His research work focused on woody biomass policy and demand, forest and land-use markets, forest carbon inventory and accounting in the southeastern United States and comparative regions. Will also worked as a forest market analyst intern for Forisk Consulting in Athens, Georgia in 2014.

ACKNOWLEDGMENTS

I would first like to thank the members of the Southern Forest Resource Assessment Consortium (SOFAC) and its Co-Directors Drs. Robert Abt and Fred Cubbage for supporting research related to this paper. Their support was instrumental to my work, and made the decision to continue studies at North Carolina State University an easy one.

I want to especially thank Dr. Robert Abt for serving as my primary advisor through my graduate studies and research. The direction and support he provided while acting as a professional role model to me was invaluable and made my graduate studies experience both insightful and worthwhile. I give additional thanks to my committee members Drs. Fredrick Cubbage and Dennis Hazel for their important support and feedback. I also want to thank my Graduate Program Coordinator, Sarah Slover for a great deal of administrative help and advice, as well as the Electronic Thesis and Dissertation Editor for the workshops and editing that aided finishing this paper.

My family and friends deserve much credit for their support and motivation that helped me follow-through and finish my work. I want to thank my mother Rose, my father Jim, and my brother Eddie for the inspiration, motivation and love at all times leading up to and during my studies. I owe further special thanks to my friends Amanda Holdman, Landon Robinson, Nick Mountcastle, Mary Elmer, Anna Duden, and Terry Coleman whom were of special importance in encouraging my work while helping me maintain my sanity.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER ONE: INTRODUCTION

Introduction and Statement of Purpose

Interest in renewable energy has increased scrutiny regarding the carbon neutrality of woody biomass based energy. The European Union's (E.U.) acceptance of wood-based energy has created an annual wood pellet production capacity of over 9.5 million metric tons in the southern United States in 2016 alone (*Monthly densified biomass fuel report.* 2016) While there are many factors involved in calculating the carbon balance of using woody biomass a fuel source, the crux of forest biomass being sustainable is how forests respond to the addition of demand and harvesting for biomass, primarily in regards to carbon stocking. As with any other energy source, there are different methods of woody bioenergy production with many variables, which likely result in different carbon balances. Understanding how forest carbon stocking is affected by the specific real world variables used with woody biomass production is critical to assessing the level of carbon neutrality and for designing and approving policy supporting the system in an area. A large amount of woody biomass production is occurring in the form of wood pellet production in the southeastern United States. The E.U. passed the Renewable Energy Directive (RED) in 2009 which requires a 20% reduction of carbon emissions as well as requiring 20% of all energy consumption to be sourced from renewable energy by 2020 (REGULATION (EC) No 443/2009 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL. 2009).

Stricter targets are expected to be issued closer to the 2020 goal. A combination of resource availability, supply chain infrastructure, and carbon life-cycle advantages have pushed the demand for biomass to be sourced not from land dedicated to bioenergy production, but from already established forest and wood product industries. The biomass feedstock procured for pellet production has predominately come from pulpwood-grade roundwood with some limited use of logging residues (Carter, 2013). The southeastern U.S. has a large abundance of roundwood that falls into two broad species groups, softwood (generally gymnosperms) or hardwood (generally angiosperms) each with its own ecological, market and carbon sequestration characteristics. This study examines the difference in forest carbon impacts resulting from different species mixtures of the biomass feedstock in the southeastern U.S. through comparison of modeled biomass and baseline scenarios.

As woody biomass production in the southeastern U.S. becomes increasingly more popular in order to meet demand for sustainable bioenergy, the specific carbon benefits and costs of the complex process are being examined in greater detail. Recent life-cycle analysis (LCA) and studies attempting to measure or estimate the carbon debt or benefits of the system have made note of the importance of examining forest product and land-use market impacts on carbon sequestered in forestlands (Daigneault, Sohngen, & Sedjo, 2012; Helin, Sokka, Soimakallio, Pingoud, & Pajula, 2013; Searchinger et al., 2009; Stephenson & MacKay, 2014). While earlier papers challenged the notion of woody biomass as a carbon neutral fuel source, critical review highlighted that the carbon intensity of wood for fuel varies with key parameters and assumptions, with some estimates approaching carbon neutrality, and most showing significant improvements relative to fossil fuels (Chum et al., 2011; Johnson, 2009). More research subsequently acknowledged that variables of analysis such as geographic location of forests, scale of forests examined, time frame, and feedstock material important assumptions that affect the outcome (K. L. Abt, Abt, & Galik, 2012; K. L. Abt, Abt, Galik, & Skog, 2014; R. C. Abt, Galik, & Henderson, 2010; Bauen et al., 2009; Birdsey, Pregitzer, & Lucier, 2006; Cooper, 1983; Earles, Yeh, & Skog, 2012; Galik, Abt, & Wu, 2009; Helin et al., 2013; Jonker, Junginger, & Faaij, 2014; Lamers & Junginger, 2013; Marland & Schlamadinger, 1995; Nepal, Wear, & Skog, 2015; Newell & Stavins, 2000; Schlamadinger, Spitzer, Kohlmaier, & Lüdeke, 1995; Schlamadinger & Marland, 1996; Sedjo & Tian, 2012).

At the time of this research, industrial wood pellet production is the largest consumer of locally sourced woody biomass in the southeastern United States (International Trade Administration Industry and Analysis Staff, 2016). Observations of these facilities indicate that only specific basins, or wood procurement circles, are being targeted in the region as biomass sourced outside economically viable procurement radius would make the price of transporting the feedstock to the mill too expensive. The biomass feedstocks are often comprised primarily of either softwoods or hardwoods, but mainly roundwood with some mill and logging residues of both `species’ as well (Carter, 2013). While the Southeast has a unique ability to provide large quantities of wood, forest dynamics and management strategies will affect carbon efficiency will vary across regions, species, and time frames.

Softwood and hardwood tree species, are commonly differentiated due to their differences in biology, management, and wood use. Both wood types are suitable for bioenergy production. Softwood largely refers to wood from pine trees. Softwood tree species exist naturally in the southeastern U.S. landscape in natural pine forests and in mixed pine forests as they commonly pioneer abandoned agricultural fields and can live on a wide range of sites (Fox, Jokela, & Allen, 2004). In addition to regenerating naturally, genetically improved pine trees are often planted on cut-over sites which allows for quick establishment of pine plantations. A combination of genetics, fertilizer and herbicide use, and well understood silvicultural practices affecting planted pine makes softwood production in the southeast much faster, efficient, and lucrative. Pine plantations allow for much higher volumes of softwood to be grown on the same amount of forestland acreage.

Hardwood supply is derived from a wide range of species that differ greatly in biological requirements, growth rate, and response silvicultural practices. In the southeastern U.S., hardwood plantations are not economically viable, and thus mainly exist on test sites (Hicks Jr, Conner, Kellison, & Van Lear, 2004). The addition of biomass demand is not likely to increase prices enough to compensate for the risk, establishment, and pest management costs involved with hardwood plantations. Hardwood tree species grow naturally in a variety of forest types. Lowland and upland hardwood forest types contain nearly exclusively hardwood species, while mixed forests contain more of a balanced mixture. Some hardwoods species also exist as undergrowth in natural pine forests to the level where some volume of pulpwood is noteworthy. Combined with slower general growth rates, and difficulty establishing hardwood forests quickly, hardwood production is less likely to increase with a given increase in hardwood demand. Many hardwood species tend to live longer, grow slower and larger than softwood species, potentially allowing more carbon to be sequestered in a stand of hardwood trees than softwood.

In regards to forest harvest decisions of stands of both species groups, trees are usually harvested not when they culminate in growth, but when they culminate in value. The value is determined by the land owner or manager and is likely a combination of the value of the stumpage price of the timber, wildlife benefits, recreational or aesthetics qualities, or even the intrinsic value that the forest stand exists. Pine forests managed for softwood production, like pine plantations, are often harvested for financial returns, taking into account future growth rates, a discount rate, and value by different forest products produced from a stand. The most valuable product from a standing tree is the sawtimber roundwood, followed by chip-n-saw roundwood, then pulpwood roundwood, and in some cases then logging residues. The value of the tree for harvesting is estimated based on the volume and price of each product. A change in pulpwood prices will have much less of an effect on the harvest age of the stand, than a change in sawtimber. None the less, a change in pulpwood prices would change the total value of a stand for harvesting, and could shift the age of the stand at harvest, or the rate of harvest in regards to multiple rotations. This holds true for some managed hardwood forests as well, but a great deal of hardwood inventory is owned by smaller landowners who value their stands for a variety of attributes besides just the economic returns (Butler, 2006).

Studies that examine the carbon cycling dynamics and compare methods and results of analyses have shown the importance of using specific and realistic assumptions in calculating the impacts of forest carbon from biomass production (Johnson, 2009; Miner et al., 2014; Newell & Stavins, 2000). The gap in the knowledge involving the analysis of forest carbon impacts from biomass production lies within understanding the difference that species selection of the feedstock makes when combined with indirect market effects and silvicultural responses available within the short to medium term run in the southeast U.S.

This study attempts to increase understanding of the forest carbon implications that woody biomass species selection has the U.S. Southeast by modeling forest carbon impacts from various biomass scenarios, as well as business-as-usual baselines. The differences between biomass and baseline runs are compared and analyzed by total forest carbon over time, carbon by forest type, amount for forestland acreage, and various forest product prices.

Results from this study are used to answer the question of whether the feedstock species selection of industrial biomass production in the southeastern U.S. affects the resulting forest carbon stocking. Given the differences in growth rate, silvicultural practices, inventory, and product prices, some trend in the difference of forest carbon is expected to be observed between heavy softwood and hardwood biomass demand. If the species selection of biomass feedstock is minor or a non-factor in determining forest carbon response to biomass production, there should not be a trend in forest carbon impacts across biomass feedstock species mixtures.

While forest response is the principle factor governing the carbon benefits of woody biomass production, the forests are still only a part of a bigger equation to calculate the carbon score of woody bioenergy. This paper's research does not involve any other aspects of life-cycle analysis or comparison to fossil fuel or alternate energy production systems. Forest carbon levels are likely to change outside the temporal scope of the research in this paper. The thirty years of analysis used in this study is of importance, but does not cover a realistic timeframe for some forests to regenerate the level of carbon stocking present prior to harvest.

Biomass scenarios in this study are constructed to simulate the feedstock characteristics across a hypothetical set of locations in the southeastern U.S. where industrial wood pellet production mills are typically operating. Results from with-biomass scenarios are compared to without-biomass baseline scenarios that include a set of assumptions about the economy, carbon and woody bioenergy policy and regulation, and growing conditions of forests in the geographic area for thirty years.

This study only examines the forest carbon impacts from woody biomass production. There is much interest and numerous studies that aim to estimate the total atmospheric carbon impacts from woody biomass and the export and use of North American wood pellets for European Union bioenergy production (R. C. Abt et al., 2010; Katers, Snippen, & Puettmann, 2012; Magelli, Boucher, Bi, Melin, & Bonoli, 2009; Stephenson & MacKay, 2014; Zanchi, Pena, & Bird, 2012). Life-cycle analysis studies of such a process incorporate several other key components of carbon flux, most notably, and combustion carbon emissions compared to fossil fuels. Results and conclusions about forest carbon in this study should not be interpreted as assessments of the overall carbon score of any wood bioenergy system.

CHAPTER TWO: LITERATURE REVIEW

Introduction

Forests are a major pool for carbon in the global carbon cycle, containing an estimated 861+/- 66 Pg of carbon which comprises nearly 80% of all terrestrial carbon, and 40% of all below-ground carbon (Dixon et al., 1994; Pan et al., 2011). Another study estimated that 60% of the above-ground carbon is located in commercial growing stocks (Earles et al., 2012). Understanding how forest use affects this massive pool of carbon is important in managing carbon emissions in regards to global climate change. Wood has long been a primary fuel source for civilizations, but detailed research on carbon sequestration and bioenergy use of forests at least dates back several decades ago and has increased along with research related to anthropogenic climate change (Miner et al., 2014).

Research focused on forest carbon in North America has increased with the expansion of biomass production for industrial wood pellet exports to Europe in order to meet emissions standards set by the EU's Renewable Energy Directive (K. L. Abt et al., 2014). The bulk of biomass production in the United States is based in the southeastern U.S. (Forisk Consulting, 2014; (K. L. Abt et al., 2014). The cost-effectiveness and carbon benefits of woody biomass from southeast U.S. forests are being examined to evaluate continued support of EU policies as well as potential U.S domestic policies. Regardless of location, research of the carbon benefits of using forest bioenergy "Scenarios that minimize forest carbon loss will improve mitigation performance of forest bioenergy" (McKechnie, Colombo, Chen, Mabee, & MacLean, 2010). Research focused on understanding carbon consequences of woody bioenergy systems indicates that the net carbon emissions can vary in direction and magnitude. A woody bioenergy system could be carbon-positive, carbon-neutral, or carbon-negative, depending on the specific characteristics of the system (Galik & Abt, 2012; Lamers & Junginger, 2013; Sedjo & Tian, 2012). The potential for directional variation of carbon flux is uncommon for non-energy uses of wood, which tend to store harvested wood for a significant time period. Assessing this net result is probably carried out best through life cycle analysis (LCA) studies to track the net emissions of the extraction, processing and transportation, combustion, and most importantly the forests (Stephenson & MacKay, 2014). An estimate of total carbon flux from an LCA of woody bioenergy can then be compared with alternative uses of the same wood and forests, as well as fossil fuel or alternate energy systems in order to view the carbon cost trade-offs in investment of such a system. The scope of research in this paper, and thus the literature reviewed deemed relevant, focuses on accounting for changes in forest carbon from bioenergy production. Downstream variables that add to the emission cost of woody bioenergy that occur after harvest, as well as the emissions of the fossil fuels displaced by biomass are crucial to a LCA estimate, but not within the scope of this paper..

The cornerstone component of a woody biomass system's potential to be carbon-positive is the forests ability to sequester carbon from the atmosphere back into terrestrial pools. While general consensus in related environmental fields may have wavered between viewing woody biomass systems as carbon neutral, carbon positive, or carbon negative (Johnson, 2009), the bulk of scientific research has exposed the depth of complexity and significant variable-interaction involved in what can be mistakenly perceived as a simple accounting problem at the policy level. McKechnie et al. 2011 highlights that timing plays a key factor in assessing the period of serious carbon debt occurring in the period after forest carbon release from woody bioenergy and the subsequent forest regrowth. In Schlamadinger and Marland (1996) *The Role of Forest and Bioenergy Strategies in the Global Carbon Cycle*, the authors identify that understanding changes in the forest carbon pools and forestland acreage are key to assessing the forest management role in carbon flux.

Forest carbon response will vary with local site conditions, forest type, and forest management. This paper only examines how forest carbon responds to woody biomass utilization given different species and forest wood product selection for a biomass feedstock. Other factors involved in an LCA such as extraction, transportation, processing, combustion, fossil fuel displacement, alternative carbon storage of harvested wood products are not within the scope of this paper. As the importance for understanding carbon storage dynamics of forests increased, research first focused on understanding the basics of forest carbon cycling, storage, and the costs and benefits for using woody biomass for energy. Among the key principles affecting the carbon story of woody bioenergy system is the type of woody biomass used (ie. logging residues, milling residues, roundwood, species, chips, pellets etc.), forest regrowth, and land-use change. One of the more recently important focuses of factors affecting woody biomass systems has been the role that forest and land-use markets play in affecting regrowth, forested area, and displacement of traditional wood product markets. The research in this paper examines the indirect impacts that forest product and land use markets have on forest carbon in the US Southeast with the introduction of industrial wood pellet production.

Basics of forest carbon accounting

The idea behind using forest biomass as a carbon neutral fuel source relies on the assumption that forests regenerate the carbon-containing woody biomass that is used as a fuel source. Harvesting a forest, whether it be in the form of a clear-cut or a partial-harvest, allows for another group of trees, or stand, to begin growing. Tree or forest growth as a whole, involves sequestering atmospheric carbon dioxide as woody biomass. Forest regrowth is not immediate, so the time after the carbon cost of harvest and combustion, but before the full benefits of forest regrowth is termed the “carbon debt.” In baseline comparisons, the term “carbon parity” is used to measure the time taken for forest carbon stockings under a biomass scenario to reach the carbon levels in a business-as-usual scenario. While some studies set the carbon parity point at a level where the forest is unharvested, this method makes the assumption that the forest would not be harvested for some other use. In LCA studies, the carbon emissions from forest biomass and fossil fuel use are compared generating the same amount of electricity, creating carbon benefits as soon as regrowth compensates for the relative inefficiency of woody biomass combustion compared to fossil fuel use. This level of benefits is not examined at the forest carbon level. Thus, on the forest carbon level, carbon debt occurs in the time between harvest and forest parity regrowth. The total forest carbon debt is a function of the size of the debt at any given point in time as well as the time taken to recuperate losses. The size of the forest carbon debt is a function of the initial forest carbon stocking as well as the potential for forest growth after biomass harvesting. In the southeastern U.S., biomass harvesting will likely occur on the same land as traditional timber harvesting, and prices for biomass would likely incentivize harvesting, and thus increase the rate of harvesting while decreasing the carbon stocking level at time of harvest. The carbon debt in this case would be the time taken to recuperate carbon stocking at the level of harvest, plus the amount of carbon that would have stayed in the forest without the increased rate of harvest.

Sustainable energy and life-cycle engineering work focused on how woody bioenergy emissions would compare to fossil fuels, and accounting for counter-factual scenarios of the woody biomass. As soon as bioenergy production from woody biomass was termed carbon neutral, critics and researchers alike pointed out the problem with such an assumption ((Walker, Cardellichio, Gunn, Saah, & Hagan, 2013). While the basic idea behind the carbon-neutrality of bioenergy was that biomass would be regrown, sequestering carbon from the atmosphere, biomass harvested from pre-existing stocks would increase carbon emissions as biomass is less efficient fuel than most fossil fuels. Important factors including where the wood was sourced from, what kind of wood was used, alternate uses of the biomass, generation efficiency, fossil fuel displacement, and biomass regrowth were highlighted as key factors in determining the carbon neutrality of such a system (Walker et al., 2013). This work further highlighted the potential positive or negative effects of carbon output that woody bioenergy would have as an alternative fuel source.

Timing

While the previous research continued, the timing of these benefits is of more particular importance. Using wood for energy does not add carbon to the biosphere the way that burning fossil fuels does, but sequestration via forest regrowth takes considerably more time than annual crops and short rotation coppicing (Agostini, Giuntoli, & Boulamanti, 2013; Lamers & Junginger, 2013). The cause for the concern, even at the forest carbon level, is that the delay for forest to sequester carbon released from biomass harvesting could cause a negative forest carbon balance. The time period when a negative carbon balance from woody biomass exists risk leads means a temporary increase in atmospheric carbon, adding to increased global climate change effects, and jeopardizing policy targets (Helin et al., 2013; Lamers & Junginger, 2013).

Forest stand growth curves with harvest removals are often used to demonstrate the concept of a carbon deficit but do not consider an affected landscape comprised of many different stands (Walker et al., 2013). Since the growth and harvest cycles of all the stands as well as the same stands in scenarios with and without biomass differ at the same point in time, an overall average of the carbon difference at a particular point better captures the carbon impact of a biomass scenario (Matthews et al., 2012).

Land-use change and forest markets

Understanding the specific geographic area and its history of land use is imperative to analyzing the effects of forest management on the carbon balance in regards to bioenergy production (Schlamadinger & Marland, 1996). The rural land in the Southeast historically has been largely held by private owners and with high competition for agricultural and forest land-uses (Alig, 1986; Butler, 2006). It has been noted that many carbon assessments of wood biomass systems have omitted considerations of forest as well as land-use market and investment factors (K. L. Abt et al., 2014; Galik & Abt, 2012; Miner et al., 2014; Sedjo & Tian, 2012). Failing to account for market effects and impacts in a forest carbon study, results in failing to account for carbon stocking changes due to land-use response, forest management, forest product output (residues, roundwood, roundwood breakdown of pulp vs sawtimber), and forest structure.

The primary market effect occurs with a combination of forest stumpage prices and relative land rents on marginal agricultural land in rural areas (Hardie, Parks, Gottleib, & Wear, 2000). Rural landowners are often able to convert their land to either forestland or agricultural land, depending on which land type is perceived as more valuable. Any change in forest inventory (supply) or forest product demand will change the relative relationship of these two rural land uses. The land use exchange between the two land-use types means that forestland acreage is not static, and thus an analysis of forest carbon would need to estimate the forestland acreage change to better gauge the true impacts. An accurate assessment of the landscape level forest carbon impacts from industrial woody biomass production should incorporate both the change in land-use over the period of analysis, as well as the role that forest product and land-use markets affect the forestland acreage change (Lamers & Junginger, 2013).

Accounting emissions and carbon-sequestration from land use change is major factor of capturing the carbon story of bioenergy production (Searchinger et al., 2009). Early large-scale timber models highlighted the importance of economic incentives as the dominant driver of land-use change between farmland and forest land, but only modeled forestland change as a fixed exogenous variable (Alig, Adams, & McCarl, 1998; Sedjo & Tian, 2012)(Alig et al., 1998; Sedjo & Tian, 2012). Alig et al. 1998 found through a modeling approach that endogenous acreage change had a significant effect on farm and forestland, especially in the U.S. South, a region sensitive to land reallocation due to policy and market changes. Historically, forestland acreage change has been the key driver in temperate forest carbon changes in North America (Pan et al., 2011). Econometric analysis in Hardie et al. (2000) later showed land share between farm and forest uses on rural land were predominately driven by the relevant relationship of returns and production costs of the two land uses. For example, forestland increased in rural areas where pine stumpage prices increased by more than agricultural rents, or agricultural production costs increased by a greater factor than timber production costs. Conversely, forestland contracted if pine stumpage prices decreased or if timber production costs increased by a greater margin than their agricultural counterparts. Econometric analysis of historical U.S. land-use trends by Lubowski (2008) further concluded that timberland returns were the most important factor affecting an increase in forestland acreage, while a decline in crop prices was another major factor to the expanding forestland acreage between 1982 and 1997 in the United States. It is important to note that studies show a historic trend and predict a continued net loss of rural land due to urbanization, a trend that may slow or speed up based on macroeconomic and population conditions, but is fairly irreversible. The result of this trend is a predictable loss of both farm and forestland as a whole. A change in the allocation between these two main classes of rural land-use may, however, lead to a relative increase or decrease in land use compared to a baseline rather than a net increase of either land-use. It is possible that changes in rent or costs of either land-use are great enough to increase net acreage of either.

While the evidence that an increase in forest products leads to an increase of the share of rural land or net acreage of forestland, there is no implication of an increase in carbon from that statement. In fact, studies have shown that a strong market for biomass would decrease forest rotation times and thus the average standing volume of carbon in a particular stand of trees (Cooper, 1983). Studies that have considered endogenous, variable forestland acreage change, however, show results that indicate that the increase in forestland acreage offsets reductions in average carbon stocking per hectare across similar forest types in the U.S. South. The increase in carbon on the landscape level is due to the general higher carbon stocking of forests compared to the previous land-use, usually marginal agricultural land (afforestation), and a change in forest management to high-intensity plantations that regrow wood faster than previous forest types (K. L. Abt et al., 2012; R. C. Abt et al., 2010; Nepal et al., 2015; Schlamadinger et al., 1995).

Forest type and management

In the U.S. Southeast, where regular forest harvests are part of the land use history, it is important to compare traditional harvest to more intensively harvested forests, than to consider no harvesting at all (Schlamadinger & Marland, 1996). While the amount of forestland acreage on the landscape in result of introduced biomass demand is an important factor affecting the carbon stocking in forests, the kind of forest in both biological structure and management system is important as well. Managed forests operating for maximum sustained yields contains on average 30% of the maximum above ground stem carbon, typically the largest pool of carbon in forests (Cooper, 1983). Managed forests can offset these reductions in carbon storage through increased soil and litter additions of carbon from an increase in harvesting (Dewar, 1991), increased likelihood of forested land-use, and storage of carbon in wood products or displacement of fossil fuels.

Some of the previous studies that examined forest and land-use market effects on the share of forestland acreage also reported increased acreage of pine plantations (K. L. Abt et al., 2012; R. C. Abt et al., 2010; Nepal et al., 2015). The southern U.S. has a history of establishing pine plantations on marginal agricultural land (Birdsey et al., 2006). Both theoretical and modeling research that focuses on forest management response to greater woody biomass demand suggests an increase in abundance of intensively planted pine forests. While there may be many impacts on wildlife, biodiversity, nutrient balances, and land-ownership, biomass supply and forest carbon storage are likely to increase in a medium to long-term period of analysis (Berger et al., 2013; Smith et al., 2012).

An increase in use on certain forest types may also cause loses in carbon. An examination of previous land-use of many pine plantations by Fox et al (2003) indicates that in additional to afforestation, pine plantation acreage often increases at the expense of natural pine forests. The conversion of natural pine to planted pine forests should be expected to increase growth rates and higher forestland rents, holding forest product prices constant, but would also result in shorter rotation periods and potentially smaller maximum stocking levels in several forest carbon pools.

A study by R. Abt et al. (2010) reported that hardwood forests lacked the same ability to increase acreage due to an increase in demand because supply response is restricted by the difficulty of establishing or converting forest to hardwood-dominant production in a short period of time. Many species of hardwoods are not easily planted, and there is little historic precedent for large-scale implementation of intensive hardwood-biomass production in the U.S Southeast (Hicks Jr et al., 2004). Besides a lack of ability to rapidly add forestland acreage containing hardwood supply and a history of being intensively managed, many hardwood-dominant forest types have larger maximum potential volumes and natural regrowth rates. If a biomass facility moved into a forest basin in order to take advantage of a surplus of hardwood stocking, the regrowth period could be dampened by limitations in hardwood management.

In addition to the silvicultural challenges of managing hardwood biomass supply, there are different management objectives in many hardwood forest types that limit a potential supply increase of hardwood biomass. With much of the forested land in the Southeast belonging to small, private owners, the value of forested land is more complex than merely a function of maximizing economic land rent (Butler, 2006). Hardwood forest types are often more valued for aesthetic, intrinsic, and recreation than softwood forest types, which are often primarily managed for financial investments (Bengston, Butler, & Asah, 2009). This addition of non-economic values for hardwood forest types make existing hardwood forests less likely to respond in management regime to increases in economic incentives.

CHAPTER THREE: METHODS

Overview

The purpose of this study is to better understand how woody biomass utilization for bioenergy production affects forest carbon in the southeastern United States. More specifically, this research aims to answer the question, how does the feedstock species selection from added biomass demand affect forest carbon stocking given current understanding of forest and rural land-use markets in the region for the purpose of and within the context of the current research outlined in the previous chapter. In order to address the research question, this study creates six biomass scenarios with different species combinations for the biomass feedstock and a baseline scenario with no added biomass demand for comparison and measures the forest carbon on the effected landscape. Output data are used to model resulting forest carbon from added demand of biomass between the different species mixes using the SubRegional Timber Supply (SRTS) model.

Dataset

Input data for this research used to represent the forest inventory characteristics was sourced from the United State Forest Service's (USFS) Forest Inventory Analysis (FIA) dataset which is publically available from the USFS upon request. FIA data is panel data collected annually from fixed field measurement plots which is then regressed over geographically-similar basins or FIA survey units to extrapolate inventory data. Any given year's FIA data set may be an aggregate of data collected from different years, which varies based on individual state survey frequency, and timing of the report. Key biological forest data used in SRTS include inventory, growth, and removals classified into relevant five-year age classes, management type, species group, and land ownership categories.

All inventory estimates in this study are modeled on SRTS data version 26, an amalgamation of FIA survey plot data from thirteen southeastern states collect between 2000 and 2012. The specific dates of data used by each state can be found in Table 1.

Table 1 Range of FIA data year by state.

STATE	Years of Plot Measurements	STATE	Years of Plot Measurements
Alabama	2001-2011	**North Carolina**	2002-2011
Arkansas	2006-2011	**Oklahoma**	2007-2011
Florida	2001-2011	**South Carolina**	2007-2011
Georgia	2004-2011	**Tennessee**	2005-2012
Kentucky	2005-2012	**East Texas**	2005-2011
Louisiana	2000-2006,2009-2011	**Virginia**	2008-2012
Mississippi	2005-2011	**Overall**	**2000-2012**

Forest carbon estimates are derived using the USFS's FORCARB lookup tables which estimate and break down carbon into the five carbon pools: live above-ground, live below-ground, dead, litter, and soils (Heath, Nichols, Smith, & Mills, 2010). FORCARB lookup tables are built on data collected from ecological studies that measured stocking in different forests and forest carbon pools as well as the dynamic interactions of those carbon pools. The table is then filled out in five-year age increments using carbon projection equations.

Modeling Software

Simulations were done using the SRTS model 3.7. SRTS was originally developed to project timber inventory in total volume for softwoods and hardwoods. The core SRTS model approach is using FIA area, growth, and removal data by forest management type data, and then combining theoretical supply and demand curve interactions to project inventory, removals, and product price. The SRTS model framework is a combination of a very detailed biological forest inventory model and a basic first-order supply and demand economic model. SRTS operates by constructing both supply and demand curves for the stumpage market of given timber products.

The stumpage market supply curve is modeled as a function of product stumpage price and the forest inventory at a given time for a given product. SRTS uses a demographic biological model to project a detailed inventory of product volume by age class, species group, acreage, management type, ownership, and growth rate in subregions using the USFS' FIA data. Historical data and econometrically-derived trends regarding harvest rates, and product supply at various traded prices allow for a supply curve to be constructed that displays the volume of a certain product supplied at a given price. Supply-curves are shifted by the modeled inventory product distribution using empirically estimated growth trends from the FIA data and, harvest distributions.

After using current harvest and price as a starting point, demand is shifted by the exogenous demand shifts, while supply is shifted by product inventory change from the biological model. SRTS model employs a binary search to find a market clearing price or equilibrium where the two curves meet in each year.

Figure 1 displays a graphic interpretation of how supply and demand curves are constructed, shifted, and equilibrated. The inventory is then grown out by the biological model in SRTS and a new starting inventory for the next period is reported for the equilibrating process to occur again with the additional consideration of the current product prices. The net inventory after adjustments becomes the next year’s starting inventory, and the process repeats. Output for each modeled year is detailed, but includes forestland acreage, product harvest and inventory volume, forest carbon pool stocking estimates by region, forest management type, and ownership.

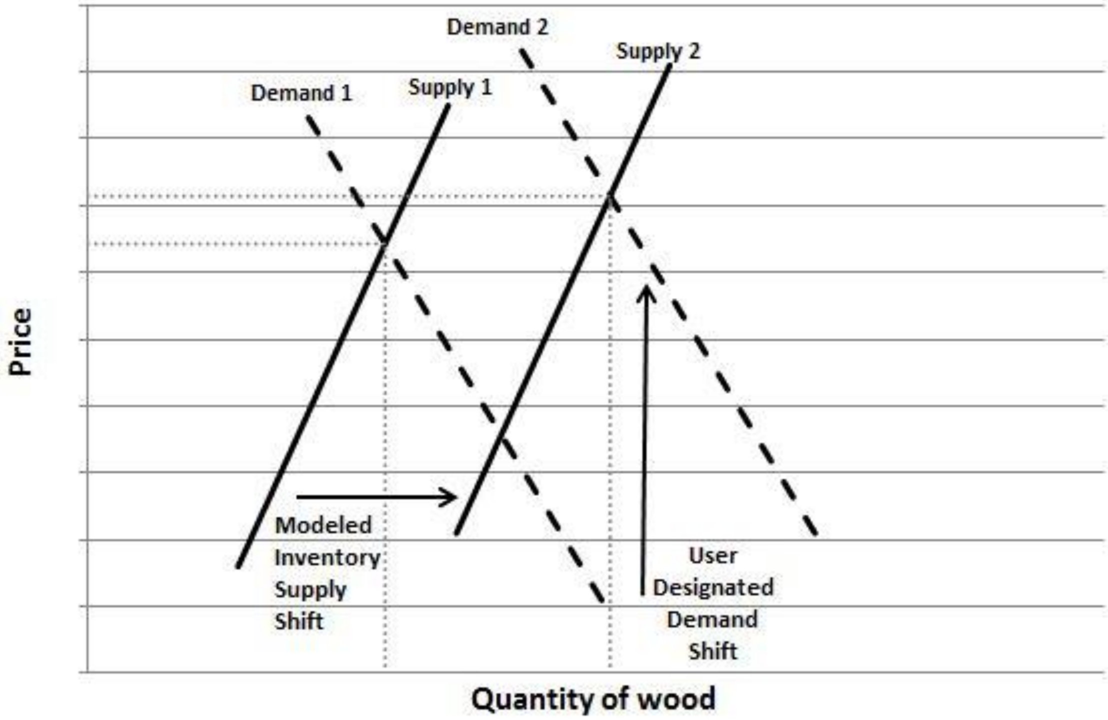

Figure 1 Graphical representation of SRTS supply and demand calculation

The supply and demand graph in Figure 1 is a theoretical example of how the SRTS model uses a user-input constructed demand curve and a forest market supply curve to determine a market clearing price. The initial market clearing price at the intersection of the demand curve one and supply curve one for any given year. For the next year, a new demand curve is constructed given input from the modeler. In this case, the level of demand is greater than the year before, so the demand curve is moved out and displayed as demand 2. The demand curve is shifted in this paper as extra demand is added in the biomass scenarios. The supply curve also shifts since inventory has changed as new forest growth and removals have been added, but the supply curve shift is completely changed by the model. The new market clearing price becomes the intersection of these new demand and supply curves.

In this study, markets factors were only analyzed within the 60 mile procurement radius of where the forest inventory would be affected by harvesting. Using only the procurement radius compared to a larger, surrounding region and basins ignores the potential for leakage into surrounding markets. Leakage would dampen price changes by distributing the demand into other markets. Larger regions of analysis mask impacts of demand and price change by distributing demand and harvesting into nearby markets, allowing the market impacts to ripple through out a region. Smaller regions of analysis constrain impacts to fewer markets, which amplifies the price and demand effects.

Scenario Development

Examining only the change in amount of forest carbon between different biomass demand scenarios ignores the overall context of how forest carbon is being changed as a whole. In order to demonstrate the relative impact of the differences between scenarios, a without biomass energy business-as-usual baseline scenario was created for every geographic basin which was examined. Comparing the biomass scenarios to the baseline scenario allows for conclusions to be drawn about whether a scenario is positively or negatively affecting the forest carbon side of the life-cycle analysis.

Various biomass scenarios were compared to baseline scenarios where the markets continued with 'business as usual' without added biomass demand. The difference between the baseline and the biomass scenarios allowed for results to be interpreted as the difference a scenario made to forest carbon if implemented, instead of just between the different biomass scenarios themselves.

Biomass demand was modeled as if a single industrial wood pellet facility opened up in a basin. The hypothetical facility modeled in this study required 1,000,000 green tons of woody biomass annually at peak production. This volume was determined after examining observed and announced production capacities of similar industrial facilities recorded by the Southern Environmental Law Center (SELC) and represents a moderately large capacity industrial wood pellet mill for export in the Southeast (Sackett, 2014). The procurement radius for such a facility was determined to be 60 miles. The procurement radius for the facility is considered the market boundary. In order to replicate the introduction of a large industrial wood pellet production mill starting production in a basin, production was ramped up from 0-100% over four years at 25% increments. Once production peaked and feedstock requirements reached 100% or one-million green tons, demand stayed constant for the rest of the period of analysis.

Projections are 30 years long, starting in 2009 and continuing until 2039. In the biomass scenarios, biomass demand is first introduced in 2014. The period of thirty years was chosen to capture the short and medium length impacts on forest carbon, which are largely determined by current policy and supply contracts. The longer the period of analysis, the more time there is for forest inventories to recover from impacts, thus leading to higher carbon benefits than in shorter periods of analysis. Longer periods of analysis also increase uncertainty of predictions regarding in-ground inventory, market characteristics, and policy-driven demand.

In order to capture forest inventory, market, or land market differences in the study, scenarios were run in five different locations in the Southeast. All sites, shown in Figure 2, are located in the states of Georgia, South Carolina, and North Carolina. The sites were initially chosen based on their proximity to clusters of existing and announced medium and large capacity wood pellet mills in the Southeast, but also in different geographic with different forest type compositions. While the geographic variation across sites is of interest, in this study it was used to provide variation in responses to species mix, and residue use across scenarios.

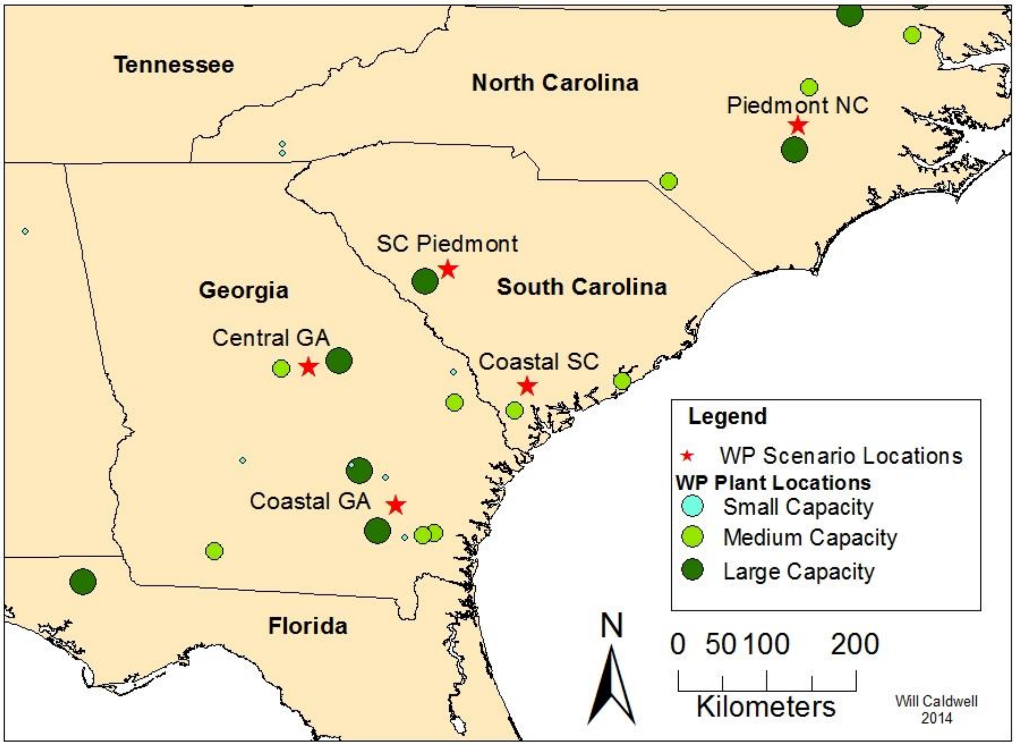

Figure 2 Map depicting actual locations of wood pellet mills and selected scenario locations in the US Southeast.

Among the biomass scenarios, three levels of feedstock species mixtures were analyzed: softwood-dominant (90% softwood, 10% hardwood), even-split (50% softwood, 50% hardwood), and hardwood-dominant (10% softwood, 90% hardwood). Research on large wood pellet mills in the Southeast prior to this study showed that feedstock was usually selected to be predominately comprised of one kind of species group (softwood or hardwood) for ease of process engineering and quality control reasons, but a small portion of wood from the other species group would be used to meet output goals. The softwood-dominant and hardwood-dominant scenarios simulate both these type of real-world scenarios, but the even-split scenario is not realistic. Instead, the even-split scenarios were included to act in sort as a species availability control, incase either hardwoods or softwoods were not abundant enough to source 90% of the demand.

Scenarios were also built to include logging residues to help analyze both the effects that logging residues have on forest carbon as well as how the impacts of logging residues differ with dominant species use. For each of the three feedstock species mixtures, two levels of logging residue use were examined. The first is zero collection of logging residue use in the woody biomass sourcing, while the second is a 15% recovery rate of all available logging residues of all species and forest harvests in the basin/procurement radius. Logging residues are analyzed by a rate of recovery instead as a portion of the total feedstock composition because of limitations on how logging residues can be incorporated into the SRTS modeling scheme. The rate of 15% was chosen because it represented a feasible recovery rate as well as a not likely exceeding the portion of the total pellet composition rate that would violate the pellet emission standards that exist in production contracts between pellet suppliers and buyers. The addition of the logging residue levels brings the scenario total to six biomass scenarios and one baseline scenario for a total of seven scenarios.

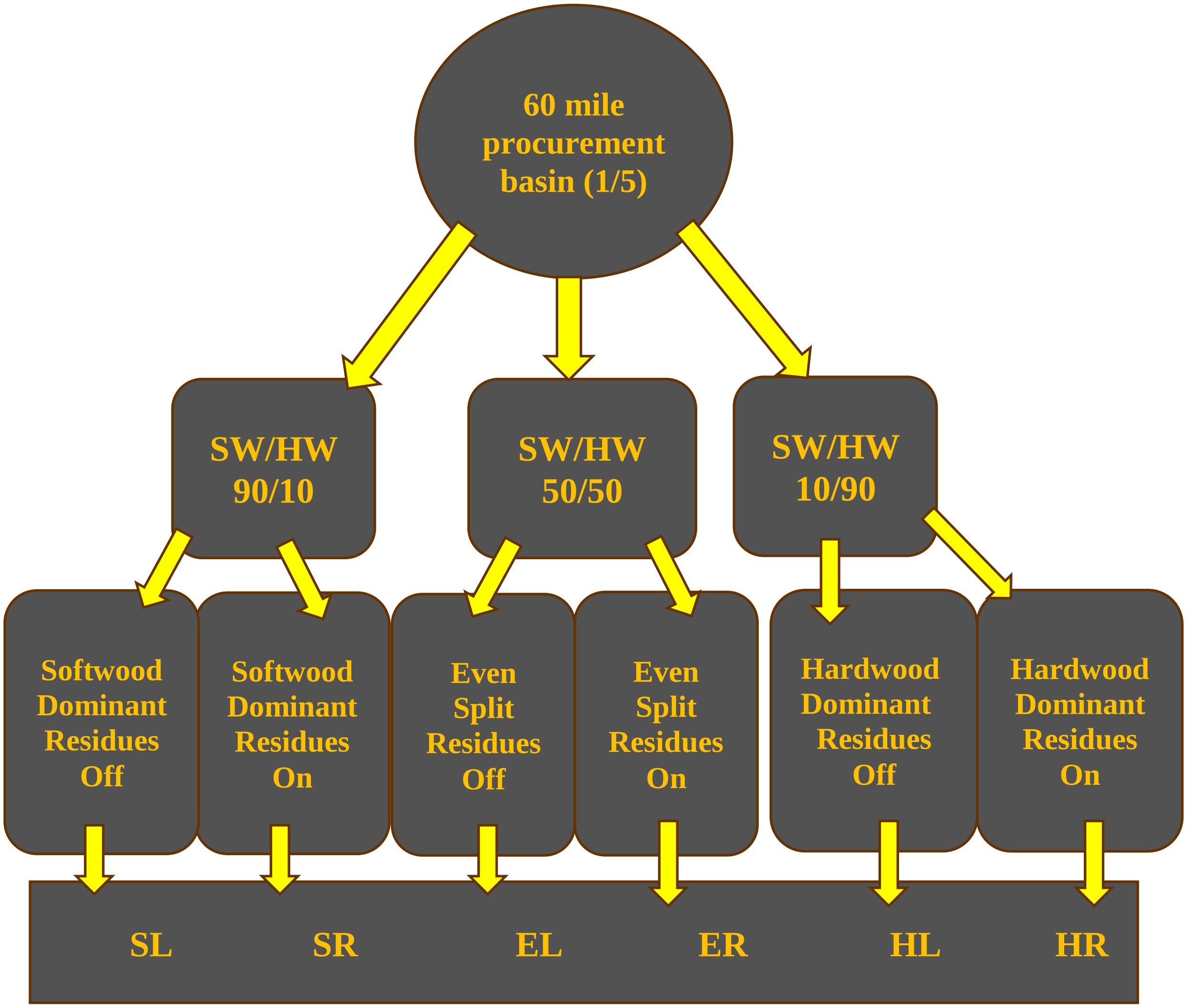

Figure 3 Flow chart depicting modeled scenarios for each geographic basin.

Table 2 Table listing of biomass scenario codes and respective feedstock variables

Code	Scenario
SL	Softwood-dominant, logging residues left on site
SR	Softwood-dominant, 15% logging residues recovered
EL	Even-split, logging residues left on site
ER	Even-split, 15% logging residues recovered
HL	Hardwood-dominant, logging residues left on site
HR	Hardwood-dominant, 15% logging residues recovered

Modeling Approach

In order to understand the difference that species selection of biomass has on forest carbon, this study includes output from 35 scenario combinations in SRTS, and compares the output. While each scenario differed in the geographic location, level or production definition of demand, the model runs between the scenarios shared a large portion of the same modeling parameters as shown in Table 3.

Table 3 Summary of SRTS model parameters for all baseline and biomass scenarios**.**

Demand Driven Runs	Start Year: 2009
Endogenous Land Use Change	30 Year Projection
Biomass Demand Run	5 Product Classes
Land-use Removals Included	Pine: Pulpwood, Small Sawtimber, Sawtimber
Plantation Growth Calibrated to Local Data	Hardwood: Pulpwood, Sawtimber
First Pine Planation Age Class of 3	

All modeled scenarios were run in only one region, then clipped 60-mile procurement radius around the specific latitude and longitude coordinate. The net inventory after adjustments becomes the next year's starting inventory, and the process repeats. Output for each modeled year is detailed, but includes forestland acreage, product harvest and inventory volume, forest carbon pool stocking estimates by region, forest management type, and ownership. All scenarios started in the year 2009 and where projected out 30 years with detailed reports recorded every modeled year.

Table 4 Table of product definitions and elasticities in SRTS for all scenarios.

Product Label	Pine	MinDBH	PctPulp	Tons/MCF	IniHarvChg	AnnHarvChg
Pulpwood		5-6.9	1	35.5	0	0
Small sawtimber		9-10.9	0.6	35.5	0	0
Sawtimber		11-12.9	0.1	35.5	0	0
Product Label	Hardwood	MinDBH	PctPulp	Tons/MCF	IniHarvChg	AnnHarvChg
Pulpwood		5-6.9	1	37	0	0
Sawtimber		13-14.9	0.25	37	0	0
Prod Label	Pine	DemPrcElas	IndSupPrc	IndSupInv	NIPFSupPrc	NIPFSupInv
Pulpwood		0.25	0.3	1	0.3	1
Small Sawtimber		0.25	0.3	1	0.3	1
Sawtimber		0.25	0.5	1	0.5	1
Product Label	Hardwood	DemPrcElas	IndSupPrc	IndSupInv	NIPFSupPrc	NIPFSupInv
Pulpwood		0.25	0.3	0.2	0.3	0.5
Sawtimber		0.25	0.5	0.2	0.5	0.5

Pine products are broken down into three products, pulpwood, small sawtimber, and sawtimber, while hardwood products do not have a small sawtimber product. The MinDBH column displays in the minimum diameter breast height (DBH) for volume consideration. The PctpPulp column displays the percentage of pulpwood obtained from harvesting trees in each product class. The tons/MCF column displays the short tonnage per thousand cubic feet of green wood. IniHarvChg and AnnHarvChg columns display the input in the rate of change of incremental and annual harvests, which is instead fixed in a separate file explained in the volume portion of scenario development. Elasticities displayed in the figure include demand price elasticity (DemPrElas), industrial supply price elasticity (IndSupPrc), industrial supply inventory elasticity (IndSupInv), non-industrial private forestland supply price elasticity (NIPFSupPrc), and non-industrial supply inventory elasticity (NIPFSupInv).

Commonly used industry product definitions were used to assigned volume per product from reported inventories. Aggregated demand elasticity across all products is set to be rather inelastic, as research suggests (R. C. Abt, Cubbage, & Abt, 2009).

These elasticities reflect several established trends. The first being that the supply of sawtimber products is more sensitive to price changes as they are in the highest price product class. Secondly, softwood inventory is more elastic for all owners because of the planting of pine forests and their rapid growth. Thirdly, non-industrial landowners are more sensitive to changing hardwood inventory with price changes than their industrial landowner counterparts.

Measurements Procedures and Instruments

Displaying only the biomass results would misrepresent the true effect of biomass production on forest carbon by ignoring the business as usual counterfactual, thus the difference between the biomass scenario and the baseline makes for a more accurate statistic when comparing results between biomass scenarios. Total forest carbon was added up across all forest carbon pools for each year across all five basins over the 30 year modeled period in the baseline and all biomass scenarios. Results were initially designed to be compared between basins with different starting inventories, so comparison statistics needed to be indexed to account for these starting differences. Indexed estimates were built by dividing the difference between the biomass scenario estimate and the baseline scenario for any given year by the starting 2009 estimate, which is the same for both the baseline and biomass scenarios. The resulting statistic is the difference between the biomass and baseline estimates of that year or period of time as a percentage of the starting level of that estimate, be it forest carbon, forestland acreage, or price. The higher the starting inventory of said statistic, the higher the same percentage represents.

In order to consolidate the thirty years of estimates for each scenario, decadal averages were used to summarize temporal trends. Since there is no difference between the baseline and biomass scenarios in the first five years of the first decade of analysis, decade one is only an average of the indexed difference of estimates in years 2014-2019. The second and third decade averages are comprised of ten years, 2020-2029 and 2030-2039 respectively. Additionally, overall statistics were used at some points in the analysis in order to compare biomass scenarios in sub-classifications of forest carbon changes. Overall or total indexed averages were calculated using the same yearly estimates that were used in the decadal averages except all estimates from the year 2014-2039 were considered.

Examining the baseline and the total of all biomass scenarios from year to year across the entire modeled period makes it easier to view the general trend of the estimates and how woody biomass affects the statistics on average as a whole. In both the baseline and the biomass scenarios, estimates may be declining or increasing, but what is more important for policy decision-making is the impact of the biomass scenarios relative to the baseline. As viewed on a line graph, the direct and magnitude, as well as the timing of the gap between the baseline and the biomass scenarios outlines the key policy-related conclusions from such a study.

Forestland acreage is measured as the amount of forestland within the 60-mile procurement radius. The change in forestland acreage occurs as rural land-use changes categories between forestland and agricultural land. The change between the categories is a function of the difference between forestland rents and agricultural rents on the land suitable for both uses. In theory, landowners will change their management to the option that has the greatest returns. In the Southeast, crop and pasture land is estimated around 20% of the total land use (Nickerson, Ebel, Borchers, & Carriazo, 2011). Marginal agricultural land was an estimated 19.5% of Georgia’s cropland (Moorhead & Dangerfield, 1998). The amount of forestland acreage on the landscape highlights role that the forest products and land-use markets play in affecting forest carbon by changing acreage.

This study also tracked the carbon and acreage changes on five forest types; planted pine, natural pine, mixed pine, upland hardwood, and lowland hardwood forests. For categorical purposes in this study, the forest types were reported as planted pine, other pine (a combination of natural pine and mixed pine forests), and hardwood forests (a combination of upland and lowland hardwood forests). Examining both carbon stocking and forestland acreage by forest type categories allows for examination of where the carbon is being gained or lost based on management and biological responses. Increased demand and prices for softwood in the Southeast is known to increase supply from planted pine forests. The study predicted that adding biomass demand will increase forestland acreage as a whole, but that the mixture of species demand will determine the allocation between forest types as different forest types contain different inventories of soft and hardwoods.

CHAPTER FOUR: RESULTS

Forest Carbon

The decadal averages over the thirty-year period of analysis for all biomass scenarios broken down by their species and residue use in Figure 4 show three general trends in the results. The first and most consistent trend is that the difference in forest carbon between the biomass scenarios and the baseline increases with time. In every feedstock combination, the average difference from the baseline increased in magnitude over each decade. The second observed trend comes from examining the results by species. The indexed average percent changes are greatest with softwood dominant use, followed by the even-split use, and finally the hardwood-dominant use with the lowest average indices. Results with the greatest amount of forest carbon were seen with greater softwood biomass demand, with a relative decrease in forest carbon with less softwood biomass demand. The third general trend among difference biomass feedstocks is seen holding the species constant and thus comparing the effect of residue use among the species mixture of demand. Forest carbon levels are higher in both the softwood-dominant and even-split scenarios when logging residues are left on site instead of being collected for biomass. Forest carbon levels are higher with demand for logging residues, however, when the species mixture of biomass demand is predominantly hardwood.

It is important to note that this is the average trend for even-split biomass scenarios among all basins. In individual basin analyses, even-split estimates fell in between softwood and hardwood dominant scenario estimates, but in some basins, the even-split forest carbon levels were negative percent changes compared to the baseline. The negative percent change does not necessarily indicate that carbon stocking from year to year, but only in comparison to the estimated carbon stocking in the baseline scenario.

Tables and figures in this chapter include two-character coded names for the biomass scenarios. All softwood scenario-dominant scenario codes starting with “S,” while all even-split scenario codes start with “E,” and all hardwood-dominant scenario codes start with “H.” The second letter of the biomass scenarios codes represents whether logging residues were used as a feedstock. The letter “L” is used to denote that the scenario assumed logging residues were left on the ground, while “R” denotes that the scenario assumed that 15 percent of all logging residues were recovered and used as part of the biomass feedstock. The scenario codes and their corresponding biomass scenarios are as follows: SL for softwood-dominant biomass with no logging residue use, SR for softwood-dominant biomass with logging residue recovery, EL for even-split biomass with no logging residue use, ER for even-split biomass with logging residue recovery, HL for hardwood-dominant biomass with no logging residue use, and HR for hardwood-dominant biomass with logging residue recovery.

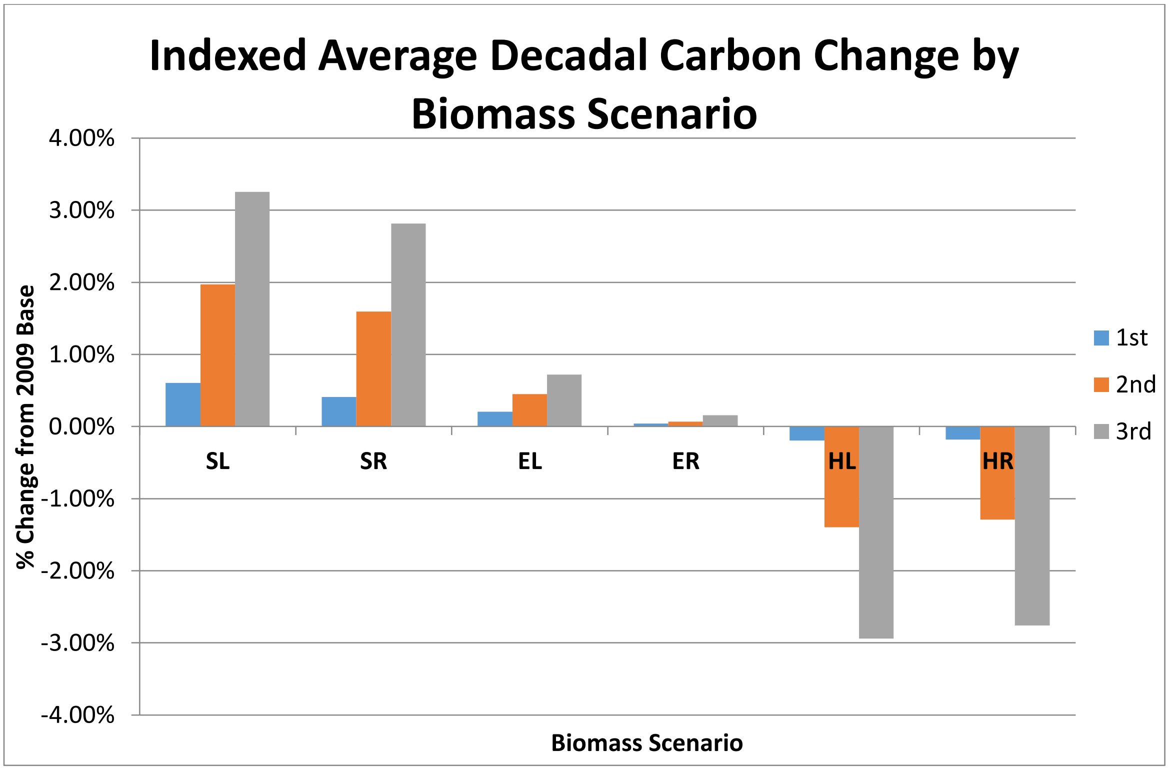

Figure 4 Indexed average decadal carbon change by biomass scenario.

As shown in Table 5, the largest indexed percent change on average occurred in the softwood-dominant, no logging residue demand biomass scenario at 3.25 percent in the third decade of analysis, and 2.15 percent for the whole period. While not as large, it is noteworthy that the largest decrease in forest carbon levels was -2.94 percent in the third decade, and -1.71 percent for the entire period of the hardwood-dominate, no logging residue demand biomass scenario. Without averaging any of the forest carbon results, the largest increase in forest carbon for any single year was 7.51 percent in the South Carolina coastal plain basin, and -8.78 percent in a single year in the North Carolina coastal plain basin.

Table 5 Average indexed change of carbon for each decade by biomass scenario.

	Biomass Scenarios					
Decade	**SL**	**SR**	**EL**	**ER**	**HL**	**HR**
1st	0.60%	0.41%	0.20%	0.04%	-0.19%	-0.18%
2nd	1.97%	1.59%	0.45%	0.07%	-1.39%	-1.29%
3rd	3.25%	2.81%	0.72%	0.16%	-2.94%	-2.76%
Total	**2.15%**	**1.79%**	**0.50%**	**0.10%**	**-1.71%**	**-1.60%**

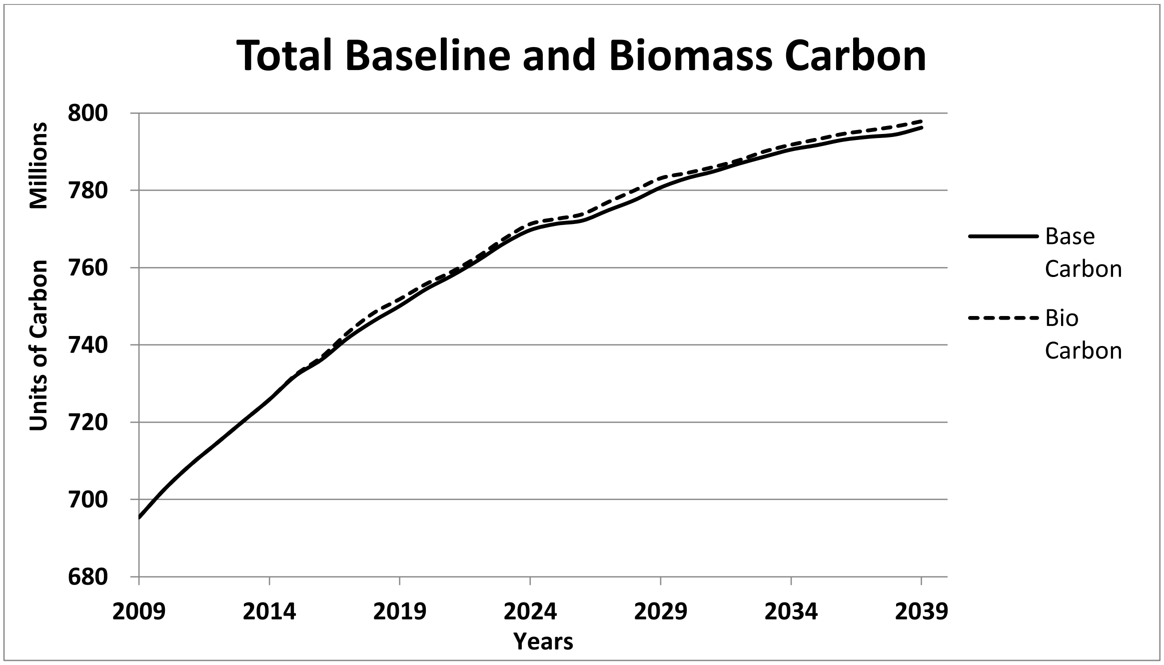

Figure 5 Totals of Baseline and Biomass Forest Carbon

As shown in Figure 5, the forest carbon baselines increased by 14.5 percent on average over the period analysis. This trend of steadily increasing forest carbon illustrates why comments about the direction of forest carbon change are misleading without reference to the baseline. Forest carbon under a biomass scenario could increase over time by any percentage less than 14.5 percent compared to the 2009 levels, but would still not result in a relative loss in carbon compared to the baseline.

On average, the biomass scenarios combined increased carbon by about 0.30 percent, although this estimate has no realistic interpretation because all six biomass scenarios would not occur at once in each location. The purpose of displaying the total average forest carbon of the biomass scenarios in a line graph is meant to show the average year to year change between baseline and biomass scenarios. The gap between the two alternatives begins with addition of demand in the biomass scenarios, and starts to stabilize in the second decade of analysis. Both types of scenarios are subject to the same general trends from year to year.

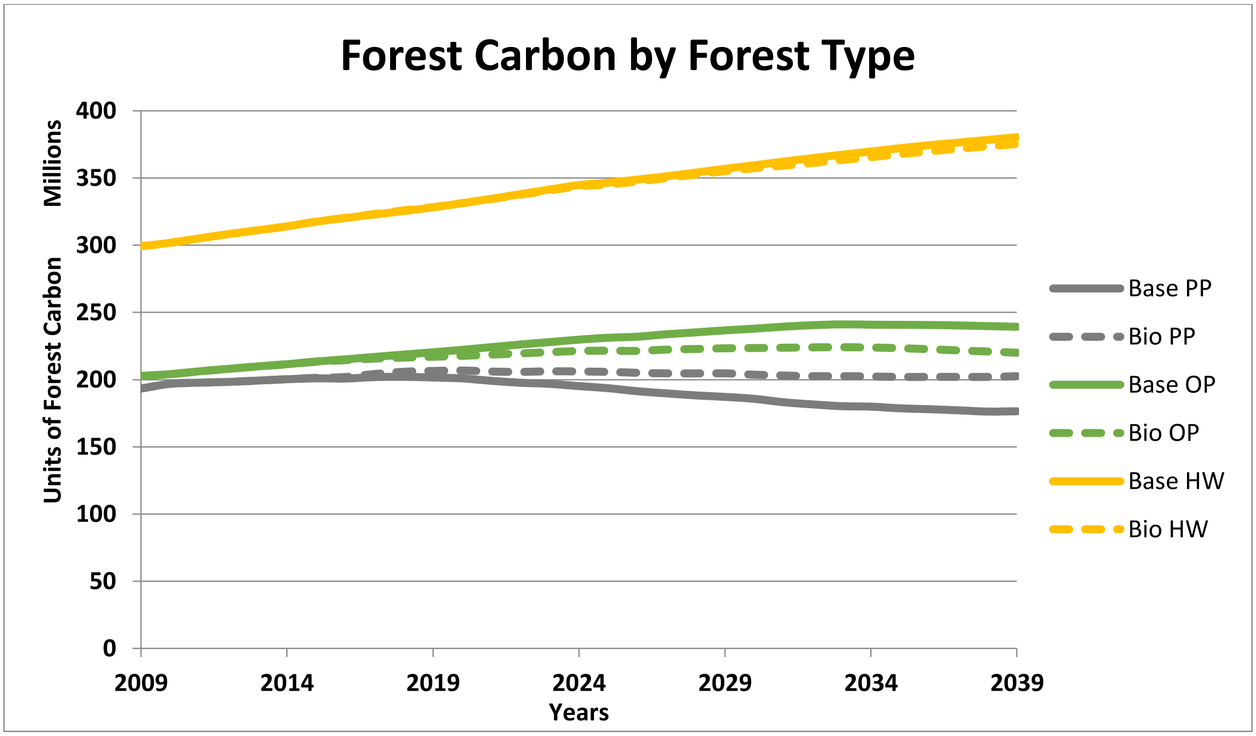

Figure 6 Line graphs comparing forest carbon between the baseline scenario and average biomass scenario on pine plantation, other pine, and hardwood forests.

The three forest types examined are hardwood forests (HW), other pine forests (OP), and planted pine forests (PP). In planted pine forests, the total carbon volume starts at about 193 million units of carbon, and slowly decreased close to 176 million units over the thirty years, for a change of -8.76 percent in the baseline scenario. On average in the biomass scenarios, carbon in planted pine forests stayed relatively constant and even increases at points before dropping down to around 202 million units of carbon by 2039 for an increase of 4.73 percent.

In the forests labeled as ‘other pine’, forest carbon starts slightly higher at roughly 203 million units of carbon, and gradually increases over time to 239 million units. That change in other pine forests led to an 18 percent increase of forest carbon in the baseline scenario. On average in the biomass scenarios, carbon in other pine forests declines and recovers to roughly 220 million units at the end of the thirty years for an increase of only 8.52 percent.

In hardwood forests, carbon levels start at roughly 299 million units and increase steadily to roughly 380 million units over the thirty year modeled period in the baseline for a 27.14 percent increase overall. Under modeled biomass demand, average forest carbon in hardwood forests increased by less than the baseline and ends up at roughly 375 million units of carbon for a 25.42 percent increase from 2009 to 2039.

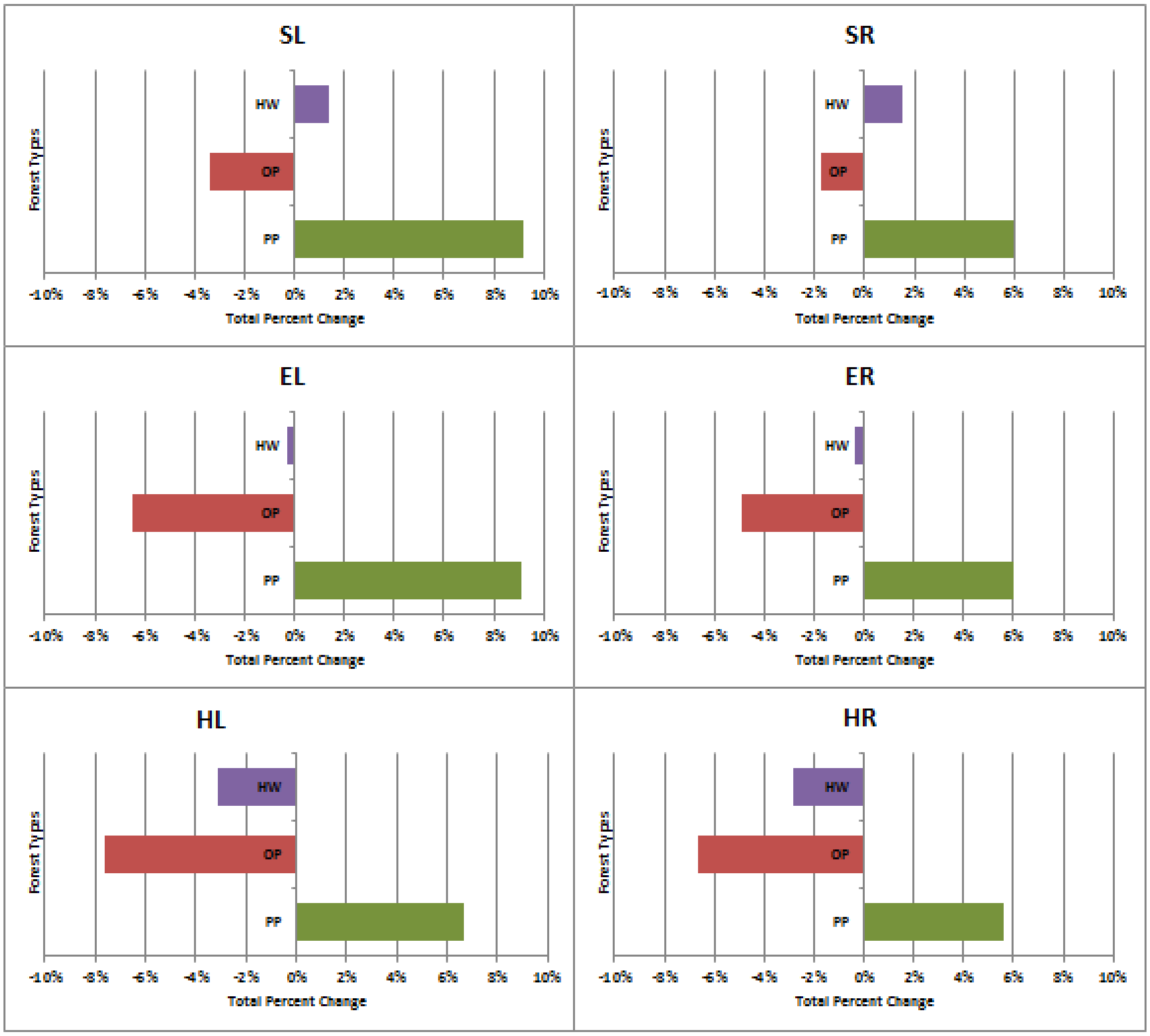

Figure 7 Average indexed change of forest carbon across biomass scenarios.

Figure 7 highlights the relative amount of forest carbon in each categorical forest types, and general trends, but the comparison between the baseline and biomass scenarios on each forest type by biomass scenario is key to the analysis. Hardwood forests gain carbon by less than 2 percent on average in both of the softwood-dominant feedstock biomass scenarios, but lose carbon by less than 1 percent in the even-split scenarios, and less than 4 percent in the hardwood scenarios. Except in the pair-wise case of the even-split scenarios, there is more carbon in hardwood forests in the scenarios where logging residues are collected and used a biomass feedstock.

Forest carbon increased in planted pine forests most dramatically of all forest types on average. In each basin, carbon increased in planted pine forests between 5-10 percent.

Counter to the case in hardwood forest types, forest carbon increases more in planted pine forests in scenarios where biomass feedstocks left out logging residues than when the logging residues were recovered. Holding the logging residue use constant, there was more carbon in planted pine forests when a greater portion of the biomass feedstock was sourced from softwoods.

Forest carbon on average, however, decreased in every feedstock combination from between around 2 percent to as much as 7.5 percent. Holding logging residue use constant, carbon in other pine forests decreased by a larger percentage the more the feedstock consisted of hardwood products for biomass. Conversely, holding the species constant, carbon losses in other pine forests are smaller when logging residues are recovered and used as a biomass feedstock.

Table 6 Average indexed percent changes in forest carbon of biomass scenarios by forest type.

Forest Type	**Decade**	**Biomass Scenarios** **SL**	**SR**	**EL**	**ER**	**HL**	**HR**
PP	1st	1.45%	0.67%	1.58%	0.79%	1.11%	0.87%
PP	2nd	7.66%	3.97%	8.08%	5.27%	5.89%	5.02%
PP	3rd	15.32%	11.05%	14.54%	9.95%	10.69%	9.07%
PP	**Total**	**9.18%**	**5.93%**	**9.07%**	**6.04%**	**6.63%**	**5.62%**
OP	1st	0.06%	0.27%	-1.03%	-0.63%	-1.35%	-1.12%
OP	2nd	-2.86%	-0.53%	-6.15%	-4.48%	-6.76%	-5.83%
OP	3rd	-6.09%	-4.11%	-10.15%	-7.84%	-12.20%	-10.73%
OP	**Total**	**-3.43%**	**-1.72%**	**-6.51%**	**-4.89%**	**-7.60%**	**-6.63%**
HW	1st	0.43%	0.35%	0.15%	0.01%	-0.25%	-0.23%
HW	2nd	1.56%	1.50%	-0.02%	-0.21%	-2.47%	-2.29%
HW	3rd	1.78%	2.18%	-0.85%	-0.75%	-5.48%	-5.00%
HW	**Total**	**1.39%**	**1.49%**	**-0.30%**	**-0.37%**	**-3.11%**	**-2.86%**

Note: Biomass scenarios are coded as follows: SL for softwood-dominant biomass with no logging residue use, SR for softwood-dominant biomass with logging residue recovery, EL for even-split biomass with no logging residue use, ER for even-split biomass with logging residue recovery, HL for hardwood-dominant biomass with no logging residue use, and HR for hardwood-dominant biomass with logging residue recovery.

Forest carbon increased compared to the baseline on planted pine forests in every biomass scenario. The story of species and residue use is not linear here. Across scenarios where logging residues are left on site, softwood-dominant demand has the largest forest carbon gain, followed by even-split, then hardwood. Scenarios where logging residues are incorporated as feedstock have smaller gains in forest carbon than their same species counterparts in all species mixes. Across recovered residue scenarios, even-split has the highest forest carbon gain, followed by softwood-dominant, then hardwood-dominant.

In other pine forests, forest carbon on the landscape is less than the baseline in all biomass scenarios. Losses are greater in pair-wise combinations where the logging residues are left on site on all species mixes. Forest carbon loses in other pine forests are greatest in the hardwood scenarios, followed by the even-split, and finally the softwood-dominant demand scenarios with the smallest amount of relative forest carbon loss.

The direction of forest carbon compared to the baseline varies among feedstock combinations on hardwood forests. Forest carbon increases in the softwood-dominant demand scenarios. Forest carbon decreases compared to the baseline on all of the even-split and hardwood dominant scenarios, with greater losses in the hardwood-dominant scenarios. Comparing the logging residue options, there is more carbon in hardwood forests when residues are recovered in the softwood-dominant and hardwood-dominant demand scenarios compared to when residues are left on site. Carbon in hardwood forests is slightly higher in the even-split scenarios when residues are left on site.

Forestland Acreage

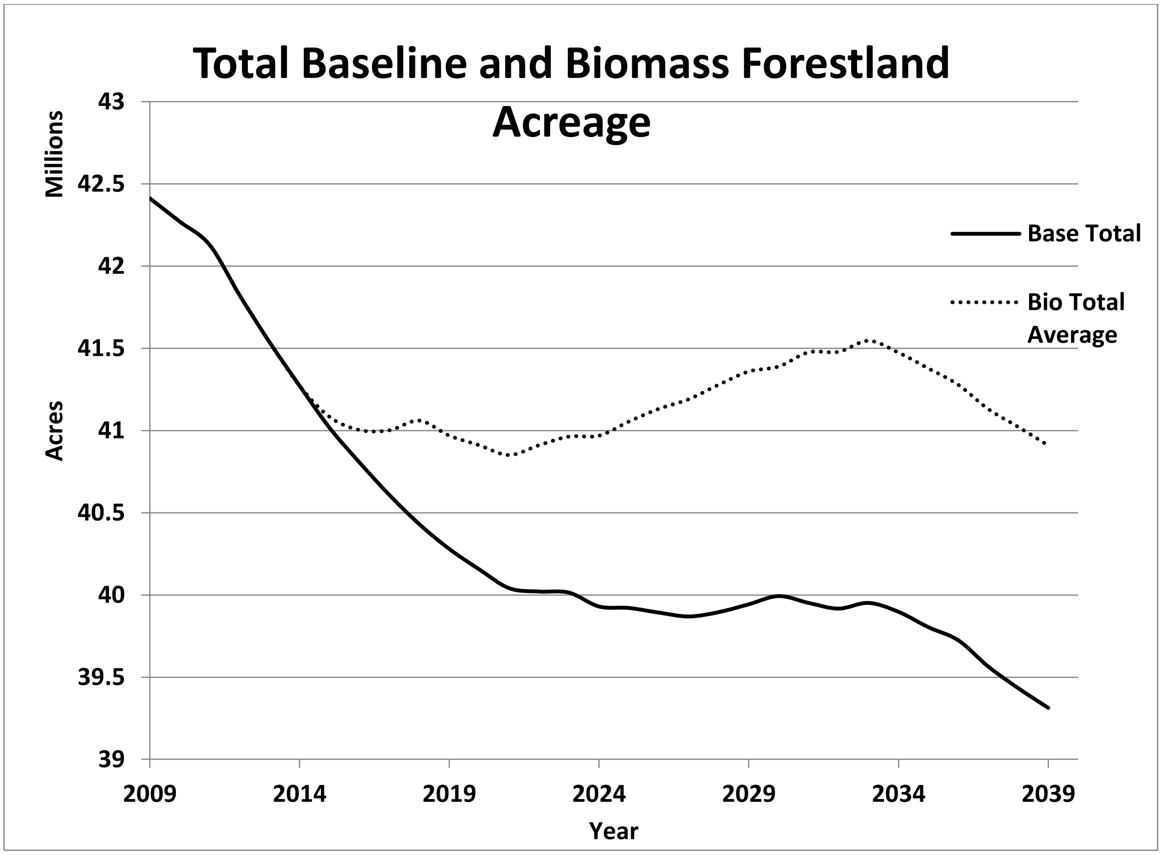

Figure 8 Line graph depicting total forestland acreage of the average biomass scenario and average baseline scenario.

Forestland acreage in all scenarios combined across the combined basins in North Carolina, South Carolina, and Georgia starts just above 42 million acres, and declines to just above 39 million acres by 2039. On average in the biomass scenarios, forestland acreage levels off, peaks, then returns to roughly 41 million by 2039. While the total average forestland acreage in the biomass scenarios is still below the initial starting level, forest acreage remains higher than in the baseline scenarios.

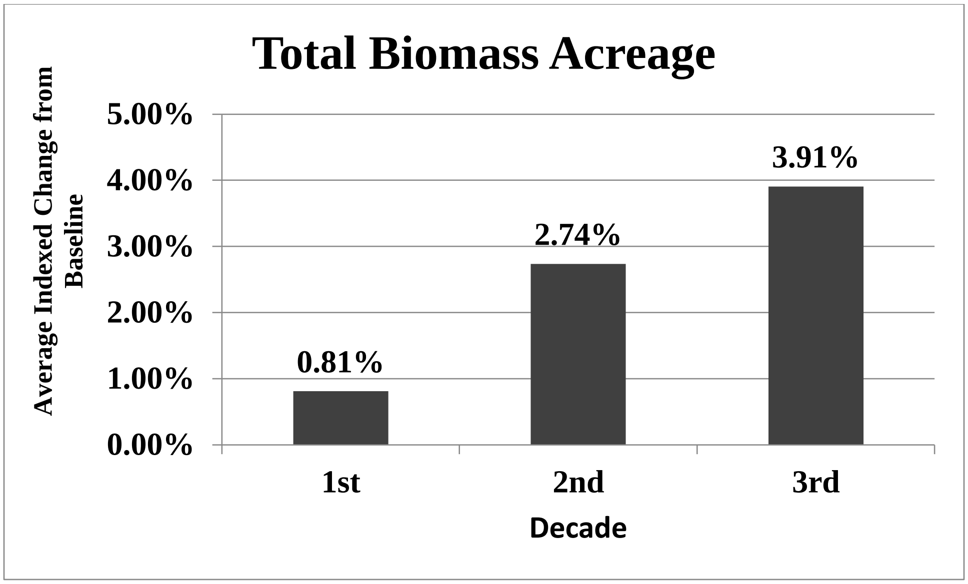

Figure 9 Total indexed percent change of forestland acreage change of all biomass scenarios by decade.

Figure 10 shows the average decadal indexed difference in forestland acreage between the total averaged biomass scenarios and the total baseline scenarios. On average in each decade, forestland acreage is higher in the biomass scenarios than in the baselines. The greater margin of forestland acreage in the biomass scenarios grows with each subsequent decade, starting at 0.81 percent in the first, then jumping to 2.74 percent in the second, and ended at an average of 3.91 percent in the third decade.

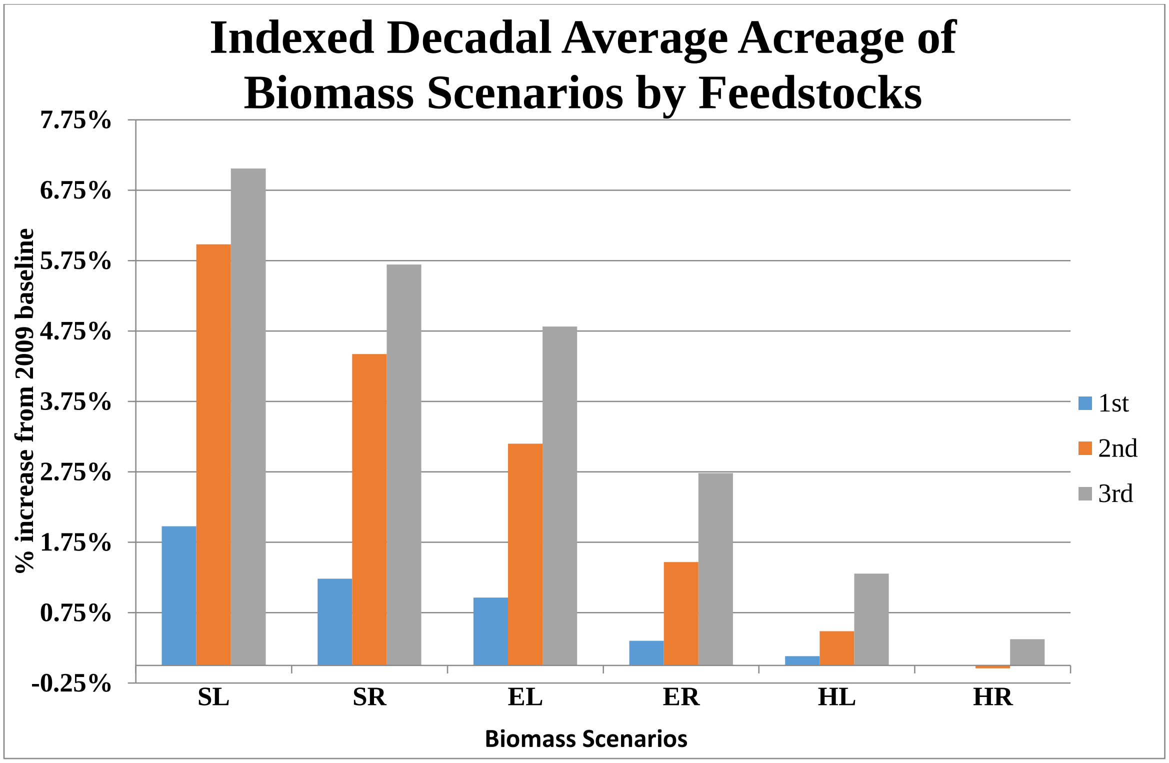

Figure 10 Indexed percent change of forestland acreage of biomass scenarios by decade.

The figure above shows indexed average changes in forestland acreage by biomass feedstock scenarios from the respective baseline runs. In all scenarios, forestland increases compared to the baseline scenario and increases by a greater extent each subsequent decade, with the exception of the difference between the first and second decade in the hardwood-dominant with logging residue use scenario. Biomass scenarios with a greater percentage of the feedstock comprised of softwoods have greater increase in forestland acreage. Scenarios that leave the logging residues on site experience greater increases in forestland acreage than biomass scenarios with the same species mix but incorporate logging residues in the feedstock.

Table 7 Average indexed percent change of forestland acreage by biomass scenario for each decade.

Decade	**SL**	**SR**	**EL**	**ER**	**HL**	**HR**
1st	1.98%	1.23%	0.96%	0.35%	0.13%	0.00%
2nd	5.98%	4.42%	3.15%	1.47%	0.49%	-0.04%
3rd	7.06%	5.70%	4.81%	2.73%	1.30%	0.37%
Total	**5.47%**	**4.18%**	**3.29%**	**1.70%**	**0.72%**	**0.13%**

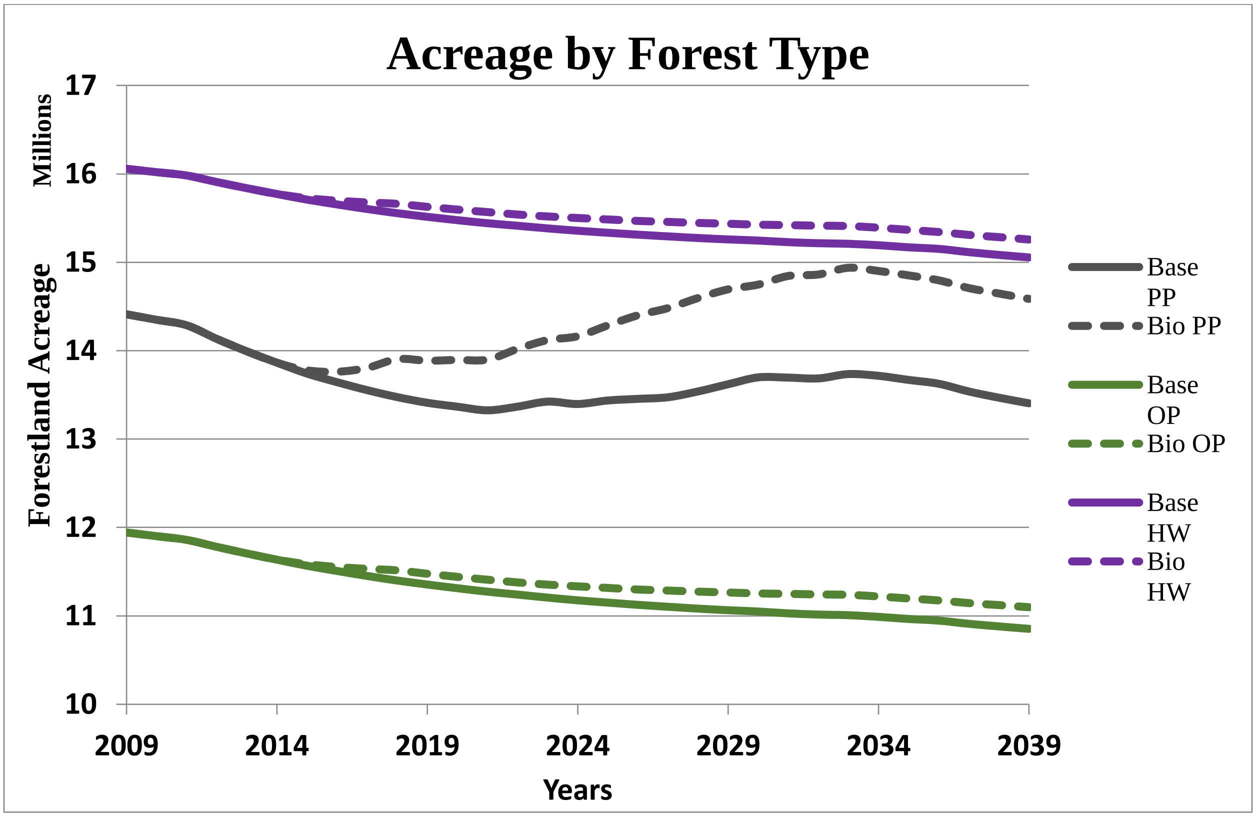

Figure 11 Comparison of forestland acreage by forest type over time

Across all basins of analysis, hardwood forest types started with the most forestland acreage with just over 16 million acres, followed by planted pine forest with just under 14.5

million acres, then other pine forests with less than 12 million acres. Forestland acreage was predicted to decline in all three forest types. Forestland acreage increased across all forest types on average with added biomass demand. The averaged planted pine forest acreage estimates actually lead to a small increase in overall forestland acreage in the later stages of analysis with a single year difference between the baseline and biomass of nearly 9 percent.

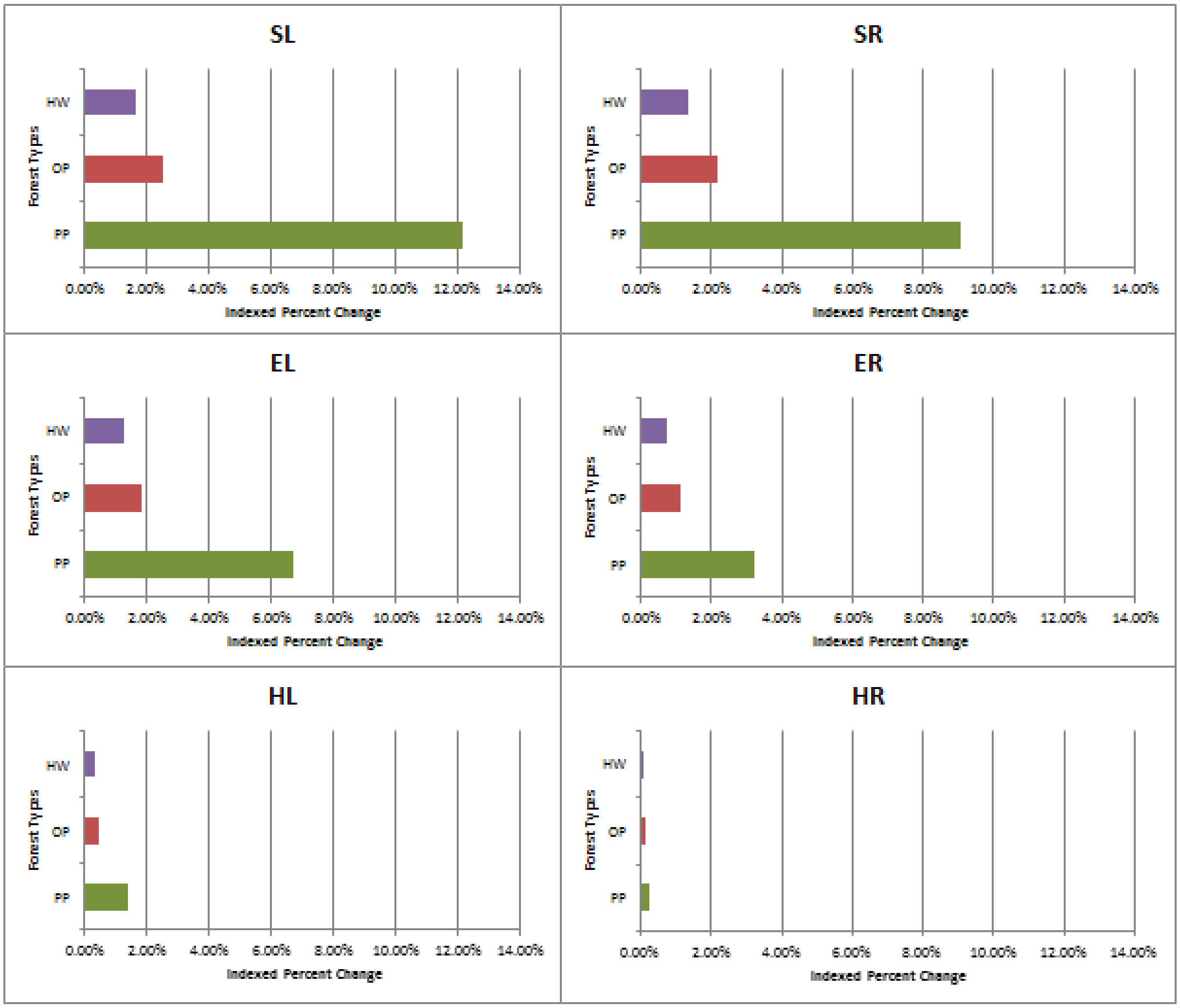

Figure 12 Biomass differences in forestland acreage by forest type

Average forestland acreage for the entire period of analysis increased among each forest type on average across all biomass feedstock scenarios. Forestland acreage gains were greatest in planted pine forests in each biomass scenario ranging as little as 0.21 percent in the hardwood-dominant scenario with logging residue use and by as much as 12.17 percent in the softwood-dominate, no logging residue use scenario. In each pairwise species mix, forestland acreage increased by a greater amount in the scenario where logging residues were left on site, rather than used as feedstock.

Table 8 Decadal averages of forestland acreage change by forest type

Forest Type	**Decade**	**SL**	**SR**	**EL**	**ER**	**HL**	**HR**
PP	1st	3.93%	2.39%	1.65%	0.58%	0.22%	0.00%
PP	2nd	13.41%	9.64%	6.40%	2.73%	0.84%	-0.17%
PP	3rd	15.89%	12.43%	10.10%	18.68%	2.60%	0.72%
PP	**Total**	**12.17%**	**9.04%**	**6.73%**	**3.21%**	**1.37%**	**0.21%**
OP	1st	1.19%	0.79%	0.73%	0.29%	0.11%	0.00%
OP	2nd	2.66%	2.19%	1.80%	35.94%	0.36%	0.03%
OP	3rd	3.16%	2.92%	2.60%	1.77%	0.79%	0.25%
OP	**Total**	**2.51%**	**2.15%**	**1.86%**	**1.13%**	**0.47%**	**0.11%**
HW	1st	0.81%	0.53%	0.51%	0.20%	0.08%	0.00%
HW	2nd	1.79%	1.40%	1.25%	0.69%	0.26%	0.03%
HW	3rd	2.03%	1.72%	1.71%	1.16%	0.52%	0.16%
HW	**Total**	**1.66%**	**1.32%**	**1.26%**	**0.76%**	**0.32%**	**0.07%**

Note: Biomass scenarios are coded as follows: SL for softwood-dominant biomass with no logging residue use, SR for softwood-dominant biomass with logging residue recovery, EL for even-split biomass with no logging residue use, ER for even-split biomass with logging residue recovery, HL for hardwood-dominant biomass with no logging residue use, and HR for hardwood-dominant biomass with logging residue recovery.

Table 9 Average indexed percent change of forestland acreage and forest carbon by decade broken down by each biomass scenario, species selection, and logging residue use.

		Biomass Combination						**Species**			**Logging residues**	
Decade	**Unit**	**SL**	**SR**	**EL**	**ER**	**HL**	**HR**	**Softwood**	**Even**	**Hardwood**	**Left**	**Recovered**
1st	Acres	1.98%	1.23%	0.96%	0.35%	0.13%	0.00%	1.60%	0.66%	0.07%	1.02%	0.53%
2nd	Acres	5.98%	4.42%	3.15%	1.47%	0.49%	-0.04%	5.20%	2.31%	0.22%	3.21%	1.95%
3rd	Acres	7.06%	5.70%	4.81%	2.73%	1.30%	0.37%	6.38%	3.77%	0.84%	4.39%	2.93%
Total:	**Acres**	**5.47%**	**4.18%**	**3.29%**	**1.70%**	**0.72%**	**0.13%**	**4.82%**	**2.49%**	**0.42%**	**3.16%**	**2.00%**
1st	Carbon	0.60%	0.41%	0.20%	0.04%	-0.19%	-0.18%	0.51%	0.12%	-0.19%	0.20%	0.09%
2nd	Carbon	1.97%	1.59%	0.45%	0.07%	-1.39%	-1.29%	1.78%	0.26%	-1.34%	0.34%	0.12%
3rd	Carbon	3.25%	2.81%	0.72%	0.16%	-2.94%	-2.76%	3.03%	0.44%	-2.85%	0.34%	0.07%
Total:	**Carbon**	**2.15%**	**1.79%**	**0.50%**	**0.10%**	**-1.71%**	**-1.60%**	**1.97%**	**0.30%**	**-1.66%**	**0.31%**	**0.10%**

Note: Biomass scenarios are coded as follows: SL for softwood-dominant biomass with no logging residue use, SR for softwood-dominant biomass with logging residue recovery, EL for even-split biomass with no logging residue use, ER for even-split biomass with logging residue recovery, HL for hardwood-dominant biomass with no logging residue use, and HR for hardwood-dominant biomass with logging residue recovery.

On average, both softwood-dominant and even-split species combinations experienced increases of acreage and carbon compared to the baseline. The average increases in acreage are greater than the average increases in carbon for the softwood-dominant and even-split species mix combinations. The two hardwood-dominant species mix combinations on average increased acreage compared to the baseline, but lost carbon in forestlands compared to the baseline. The average increases in forestland acreage are less than the average loss of carbon in the hardwood-dominant species mixes.

Both forest carbon and forestland acreage estimates increased compared to the baseline when biomass scenario results are aggregated by logging residue use. Acreage increases are greater than the carbon increases. Average increases are greater for both forestland acreage and carbon in forests in scenarios where the logging residues are left on site.

Examining the total acreage results by of all feedstock sourcing combinations, all biomass scenarios resulted in greater forestland acreage on average compared to the baseline. Scenarios that sourced more of the biomass feedstock from softwoods resulted in greater increases of forestland acreage on average compared to the baseline. Holding species-mix constant, recovering logging residues resulted in of a forestland acreage increase on average compared to the baseline. With softwood-dominant mixes, leaving residues resulted in a total average of 4.74 percent more forestland acreage, while recovering residues resulted in 3.62 percent more or 1.12 percent less than leaving the logging residues on site. In even-split species mixes, leaving residues resulted in a total average 2.85 percent more forestland acreage, while recovering residues resulted in 1.47 percent more, or 1.38 percent less than leaving the logging residues on site. In hardwood-dominant species mixes, leaving residues resulted in a total average of 0.62 percent more forestland acreage than the baseline, while recovering residues resulted in 0.11 percent more or 0.51 percent less than leaving the logging residues on site.

Aggregating feedstock scenario acreage results by species mix alone, greater use of softwood for biomass correlated with greater acreage increases. All species mixes on average resulted in more forestland acreage than the baseline. Softwood-dominant species mixes on average increased forestland acreage by 4.18 percent, even-split species mixes on average increased forestland acreage by 2.16 percent, and hardwood-dominant species mixes on average increased forestland acreage by 0.37 percent.

Aggregating feedstock scenario acreage results by logging residue use, both options on average resulted in increases compared to the baseline. Scenarios that left logging residues on site resulted in a larger increase of acreage than recovering 15 percent of the total residues on site. Scenarios where logging residues were left on site had a total average 1.01 percent more acreage than recovering logging residues as a feedstock.

All softwood and even-split species mixes, regardless of residue use came out with positive carbon gains on average compared to the baseline. Looking at each species mix, paired with their respective logging residue use, the scenario leaving logging residues on site resulted in a greater magnitude of impact. In the softwood and even-split species mixes, not using logging residues as a feedstock source resulted in less of a carbon gain on average compared to the baseline. In the softwood comparison, not sourcing a portion of the feedstock from logging residues resulted in 0.31% more carbon in forested land. In the even-split comparison, not sourcing a portion of the feedstock from LR resulted in 0.35 percent more carbon in forested land. Hardwood-dominant species mixes, regardless of logging residue use, resulted in losses of carbon on average from forestland compared to the baseline.

Examining the feedstock biomass scenarios only by their species use mix, softwood dominant species mixes resulted in 1.71 percent more carbon in forestland on average compared to the baseline. Even-split species scenarios followed with an increase of 0.26 percent on average over the baseline, while hardwood-dominant species mixes on average resulted in 1.43 percent less carbon in forests compared to the baseline.

Examining the feedstock biomass scenarios by only their use of logging residues, scenarios where the logging residues were left on site on average resulted in 0.27 percent more carbon in forests compared to the baseline. Scenarios where logging residues were recovered and used to source the biomass feedstock resulted in only 0.08% more carbon than the baseline or 0.19% less.

Prices

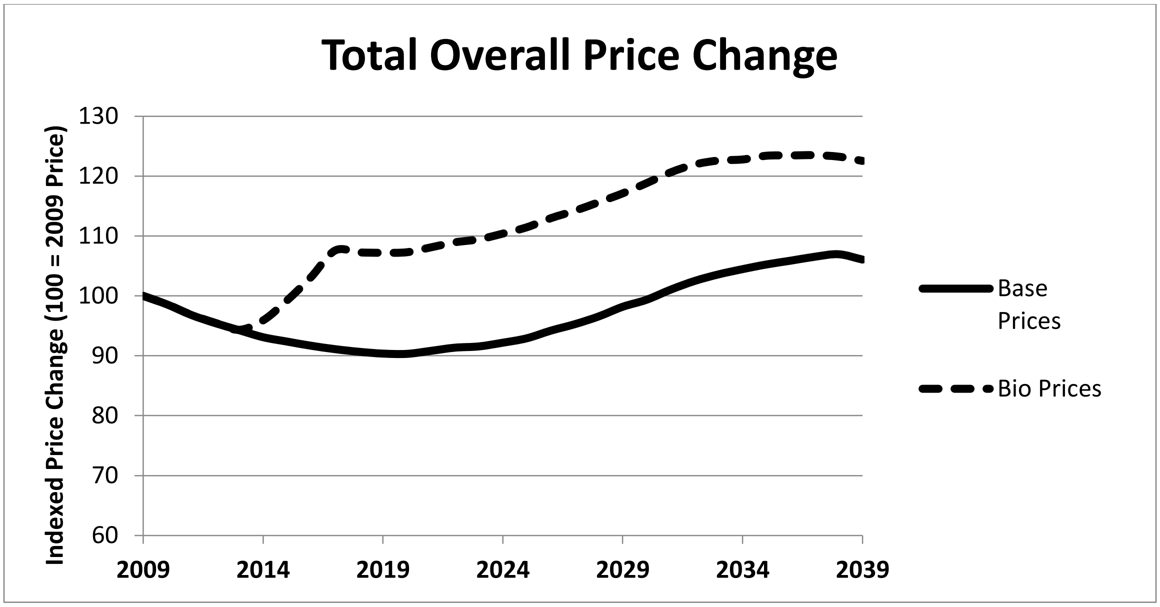

Figure 13 Total indexed price change of all forest products in the averaged baseline scenario and average biomass scenario.

The figure above shows the total indexed price change of all round-wood product classes in the baseline scenario and the average of biomass scenarios over the thirty year modeled period. In the baseline scenario, the combined average of all product prices drop nearly 10 percent around the first decade of analysis, then increase roughly 8 percent above 2009 price levels by the end of the thirty years. On average in the biomass scenarios, the combined product prices spike as biomass demand is added then follow a similar trend but staying roughly 15 percent higher, ending at roughly 22 percent higher in 2039 than the 2009 price levels.

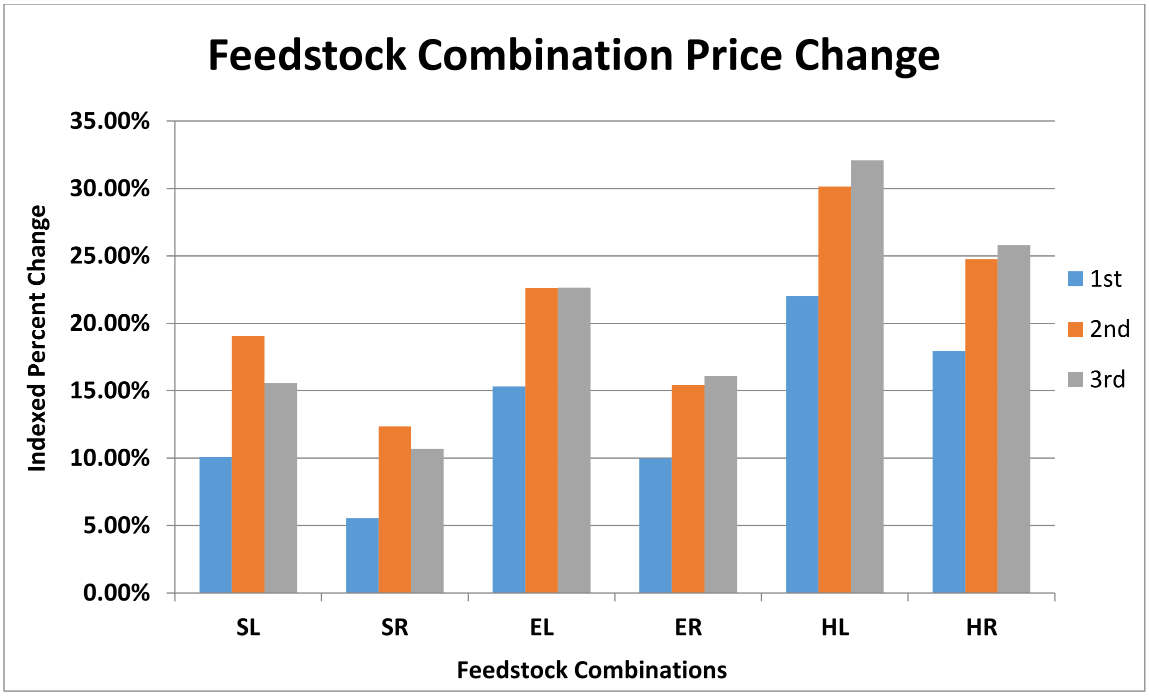

Figure 14 Average indexed percent change of all forest product prices by decade for each biomass scenario.

Figure 15 displays decadal averages of indexed price change for each of the three decades of analysis for all six of the species and logging residue combinations. Prices increase from the baseline on average in each decade across all feedstock combinations. On average, prices increased by a larger margin than in the first decade than the second decade across all combinations. Prices also increased on average by the highest margin in the third decade in both the even-split and the hardwood-dominant scenarios, while prices increased on average in the third decade by less than the second in the softwood-dominant scenarios.

Table 10 Master table of price changes.

		Biomass Scenarios*						
Product	**Decade**	**SL**	**SR**	**EL**	**ER**	**HL**	**HR**	**Variation**
SW Pulp	1st	40.66%	27.43%	21.79%	10.08%	4.51%	0.25%	40.41%
SW Pulp	2nd	76.16%	56.20%	39.48%	21.01%	7.87%	-0.03%	76.19%
SW Pulp	3rd	69.00%	53.65%	44.09%	27.87%	14.44%	4.68%	64.32%
SW Pulp	**Total**	**65.21%**	**48.58%**	**37.17%**	**21.12%**	**9.62%**	**1.84%**	**63.37%**
SW CNS	1st	0.12%	0.07%	0.03%	0.05%	0.18%	0.17%	0.15%
SW CNS	2nd	7.00%	5.53%	0.78%	-0.84%	-1.73%	-2.52%	9.52%
SW CNS	3rd	-4.18%	-0.58%	-4.82%	-4.19%	-4.44%	-6.25%	5.66%
SW CNS	**Total**	**1.11%**	**1.92%**	**-1.55%**	**-1.92%**	**-2.33%**	**-3.33%**	**5.25%**
SW Saw	1st	-0.29%	-0.13%	-0.23%	-0.04%	-0.05%	0.01%	0.30%
SW Saw	2nd	-0.33%	-0.25%	-0.43%	-0.30%	-0.23%	-0.27%	0.20%
SW Saw	3rd	0.38%	0.30%	-1.20%	-1.45%	-1.34%	-1.47%	1.84%
SW Saw	**Total**	**-0.05%**	**-0.01%**	**-0.68%**	**-0.68%**	**-0.62%**	**-0.66%**	**0.67%**
HW Pulp	1st	10.02%	0.41%	55.01%	39.81%	105.52%	89.21%	105.11%
HW Pulp	2nd	12.99%	0.60%	73.34%	57.14%	144.46%	126.31%	143.86%
HW Pulp	3rd	12.95%	0.59%	74.26%	57.42%	149.55%	130.04%	148.96%
HW Pulp	**Total**	**12.29%**	**0.55%**	**69.46%**	**53.25%**	**137.43%**	**119.18%**	**136.88%**
HW Saw	1st	-0.11%	-0.09%	-0.02%	0.00%	0.03%	0.02%	0.14%
HW Saw	2nd	-0.43%	-0.37%	0.02%	0.02%	0.37%	0.33%	0.80%
HW Saw	3rd	-0.31%	-0.47%	0.89%	0.71%	2.26%	2.01%	2.73%
HW Saw	**Total**	**-0.31%**	**-0.35%**	**0.34%**	**0.28%**	**1.02%**	**0.90%**	**1.36%**

Biomass Scenarios* spans the SL–HR columns.

**Note:* Biomass scenarios are coded as follows: SL for softwood-dominant biomass with no logging residue use, SR for softwood-dominant biomass with logging residue recovery, EL for even-split biomass with no logging residue use, ER for even-split biomass with logging residue recovery, HL for hardwood-dominant biomass with no logging residue use, and HR for hardwood-dominant biomass with logging residue recovery.

The pulpwood products are affected the most as both the largest percent changes and widest degrees of variation occur in the softwood pulp and hardwood pulp product classes.The price change is greatest in the product classes that experience the most demand from the biomass feedstock sourcing in both species and size class. The two pulpwood categories consistently have the largest percent change and variation in price. Among the same products, the scenarios that source predominately from the corresponding species experience the largest percent changes in price. For example, in the hardwood pulpwood product class, the two hardwood dominant feedstock scenarios experience the largest percent price change compared to the even-split and softwood-dominant scenarios.

Hardwood product classes are affected to a greater degree than their softwood counterparts. Hardwood pulpwood and hardwood sawtimber experience greater percent changes of price in the hardwood-dominant feedstock scenarios than softwood pulpwood and softwood sawtimber are affected in the softwood-dominant feedstock scenarios.

CHAPTER FIVE: DISCUSSION AND CONCLUSION

Results from this study indicate that the species mixture of biomass demand can affect forest carbon stocking compared to the baseline without biomass demand. More specifically, greater use of softwood roundwood biomass demand lead to larger increases in forest carbon relative to the baseline. All biomass demand scenarios resulted in relative increases of forestland acreage, however, increasing softwood-dominant roundwood biomass also consistently resulted in larger relative increases of forestland acreage. Pulpwood prices were the only product class largely affected by the biomass demand, and both softwood and hardwood pulpwood prices increased in all biomass demand scenarios compared to the baseline. Price increases by species were proportional to species consumption because the same price elasticity was used for both species groups. The relative increases of forest carbon with increases of softwood-dominate roundwood biomass demand are driven by decreased losses in forestland acreage and a shift to faster growing pine plantations. Together these factors often more than offset the loss of carbon of increased harvest.

Harvest and Price Increases

The first impact of greater biomass demand is that forest product prices and harvests increase. Increased harvesting directly removes carbon from forests and has the same initial effect on forest carbon independent of species mixture. The use of logging residues as a biomass feedstock does not change the amount of total carbon removed from forests, it allows removals from the down and dead carbon pool to meet part of the biomass demand. Sourcing part of the biomass feedstock from logging residues increases the harvestable biomass per acre, thus reducing the change in above ground carbon. The smaller effect on roundwood harvest also more importantly reduces the price effect of the demand increase.

Prices for pulpwood sharply increased in the biomass scenarios compared to the baseline. The introduction of biomass demand added competition for a rather inelastic pulpwood supply in the short-run. Even once added demand for biomass in the biomass demand scenarios stabilizes from year to year, scarcity and thus prices for pulpwood remain relatively higher in the biomass demand scenarios. Price results shown in the softwood and hardwood categories, as well as the difference between biomass demand scenarios indicate that the hardwood prices are more sensitive to a change in demand. The greater sensitivity to hardwood forest product prices indicates that hardwood supply is more constrained.

Forestland Acreage

The change in forest product prices subsequently had an effect on forestland acreage, as forestland rents are tied to the share of rural land split between agriculture and forests on marginal agricultural land in the model. Similar studies that also accounted for forest markets and land-use in regards to the addition of biomass demand found similar increased forestland acreage results (Galik & Abt, 2012; Sedjo & Tian, 2012). The model estimates the share of forestland on marginal agricultural land based on the relationship between the prices of forest rents and agricultural rents. In the land-use econometric literature, forestland rents are related to pine prices (Hardie et al., 2000; Lubowski, Plantinga, & Stavins, 2008). With softwood prices increasing in every scenario, less forestland is cleared for agriculture and more marginal agricultural land is converted to forestland. Since residue use dampens the price impact, it reduces the effect on forestland. Since softwood prices are the main rent driver in the model, the proportion of softwood in a species mix scenario determines the size of the market response.

All forest types increased in forestland acreage relative to the baseline across all biomass scenarios. They respond to the increase in price at different rates due to differences in management objectives and silvicultural limitations. Pine plantations are the most responsive since they are predominantly managed by landowners with stronger financial objectives. Other pine forests such as natural pine and mixed pine forests are less responsive, while hardwood forests are even less responsive due to a more diverse set of values held by their managers as well as silvicultural limitations of establishing hardwood forests.

Comparing the change in forestland acreage by forest type to the forest carbon change by forest type across biomass scenarios describes how the density of carbon stocking is changing. In the case of all biomass scenarios, forestland acreage increases relative to the baseline by a greater margin on all forest types than forest carbon. As forestland acreage outpaces forest carbon on all forest types, the volume of carbon per unit of area declines, regardless of whether forest carbon relatively increased or decreased as a whole. When forest carbon density declines, the carbon stocking in forests is shifted out of a smaller number of larger trees into a larger number of smaller trees. In planted pine forests, the drop in density is largely due to the large increase in planting. A large increase in young pine plantations, leads to large future increases in carbon as the trees grow. The decline of carbon density is greatest in other pine forests, since forestland acreage relatively increases in all biomass scenarios, while forest carbon relatively decreases in each biomass scenario. The relative increase of forestland acreage along with relative loss of carbon in other pine forests indicates more of a large carbon reduction on existing natural pine forestland. While the relative increase in forestland may be seen as a benefit in geographically diversifying natural pine forests, the drop in carbon density on these forestlands may be of more importance.

Since pine plantations are modeled to be more price-responsive in this study, some amount of hardwood forest types are converted to planted pine forests. That is to say that increasing forest product prices increases the pine plantation share of total forestland acreage at the expensive of other forest types, including hardwoods. Forestland acreage of hardwood forest types generally increased relative to the baseline in the biomass demand scenarios, meaning that the total increase in forestland acreage offset losses of hardwood forest type conversion. The increase in forest carbon stocking generally decreased on average, except in the softwood-dominant biomass scenario, where forest carbon actually increased with greater biomass demand. In this case, high softwood prices increased hardwood forest acreage the most, but also only placed 10 percent of the biomass demand on hardwoods. The land-use response with biomass demand led to a relative increase of hardwood forest type acreage to a large enough degree that offset the increased removals of carbon in hardwood forest types.. The increase of both forest carbon and forestland acreage on hardwood forest types with added softwood-dominant biomass demand shows a positive opportunity in adding carbon to hardwood forest types with biomass demand. Relative forest carbon gains can be sustained on hardwood forest types even with small increases in hardwood biomass demand, if a strong increase for softwood prices also creates a relative gain in the share of forestland.

Conclusions from this study come with several caveats, and results should be understood within the context of the geographic of this research as well as the assumptions in the baseline and biomass scenarios. All biomass scenarios were constructed based on general characteristics of industrial wood pellet production within a three state range of the southeastern United States. Domestic woody biomass production may not involve production of wood pellets, and thus require less roundwood for the biomass feedstock. Additionally, wood pellet production in other regions such as the U.S. Northeast or West, Canada, and Europe has different forestland ownership compositions, and land-use market dynamics. The baseline scenarios would likely also differ greatly as different regions would vary in forest inventory, prices, forest types, and management options. This not only applies to different geographic regions, but any variation in location within even the Southeast to a lesser degree. Since comparing biomass results to the baseline is imperative, considering the assumptions of the baseline scenario is crucial when evaluating results. Ideally, any attempts to estimate the forest carbon results from biomass production should include several baselines projections since predicting future conditions is uncertain, even in the short run.

While it is important to account for the assumptions in the study, it is also important to consider the biological consequences and the full life-cycle analysis of using exported wood pellets for energy production. Regardless of whether forest carbon increases or decreases, biomass harvesting reduced volume per acre, shifting the structure of biomass in forests as well as changing the proportion of forest types on the landscape. Changing the structure of forests as well as shifting the forest landscape towards less natural pine and more pine plantations will create new winners and loser. Such a change would be expected to favor species that thrive in harvesting disturbances, and younger forests at the cost of species that require older, matured forests. (Janowiak & Webster, 2010).

Forest carbon estimates from this study should provide insight towards improving life-cycle analysis modeling, however, relative gains or losses in carbon could easily be outweighed by other factors involved with using a species for biomass. Life-cycle analysis studies would capture the carbon costs and benefits of harvested wood products without biomass demand, the carbon stocking on land changed from or to forestland, the harvesting, transportation and processing, and combustion of wood pellet production and compare it to the replaced net emissions of fossil-fuel combustion.

The findings regarding the relative difference in forest carbon stocking by species mixture of added biomass demand are particularly relevant to the woody biomass production industry, biomass sustainability and life-cycle analysis, and to those studying landscape-level forest and land-use markets. The direction and magnitude of differences in forest carbon among biomass scenarios illustrates the importance of considering the specifics of forest biomass from a carbon perspective.

Future studies and analyses that attempt to model forest carbon impacts from woody biomass production should account for the species of the biomass feedstock used, and the associated market-driven change in forestland types and acreage. The impacts will vary with the forest inventory, forest and land market characteristics, and the silvicultural practices available for regeneration. This study benefited from the long term biological and market datasets and literature specific to this region, but each location in the southeastern U.S. presents a different mix of biological and market systems at each point in time. This is one reason that basin and decadal outcomes were averaged in the results section. Identification of trends across a sample of typical pellet mill locations is less likely to be biased than individual outcomes.

REFERENCES

Abt, K. L., Abt, R. C., & Galik, C. (2012). Effect of bioenergy demands and supply response on markets, carbon, and land use. *Forest Science, 58*(5), 523-539.

Abt, K. L., Abt, R. C., Galik, C. S., & Skog, K. E. (2014). Effect of policies on pellet production and forests in the US south: A technical document supporting the forest service update of the 2010 RPA assessment.

Abt, R. C., Cubbage, F. W., & Abt, K. L. (2009). Projecting southern timber supply for multiple products by subregion. *Forest Products Journal, 59*(7/8), 7.

Abt, R. C., Galik, C. S., & Henderson, J. D. (2010). The near-term market and greenhouse gas implications of forest biomass utilization in the southeastern united states. *Climate Change Policy Partnership, Duke University, Durham,*

Agostini, A., Giuntoli, J., & Boulamanti, A. (2013). Carbon accounting of forest bioenergy. *Available Online: Iet.Jrc.Ec.Europa.eu/bf-ca/sites/bf-ca/files/files/documents/eur25354en_online-Final.Pdf (Accessed on 19 August 2013),*

Alig, R. J. (1986). Econometric analysis of the factors influencing forest acreage trends in the southeast. *Forest Science, 32*(1), 119-134.

Alig, R. J., Adams, D. M., & McCarl, B. A. (1998). Impacts of incorporating land exchanges between forestry and agriculture in sector models. *Journal of Agricultural and Applied Economics, 30*(02), 389-401.

Bauen, A., Berndes, G., Junginger, M., Londo, M., Vuille, F., Ball, R., . . . Mozaffarian, H. (2009). Bioenergy: A sustainable and reliable energy source. A review of status and prospects. *Bioenergy: A Sustainable and Reliable Energy Source.A Review of Status and Prospects,*

Bengston, D. N., Butler, B. J., & Asah, S. T. (2009). Values and motivations of private forest owners in the united states: A framework based on open-ended responses in the national woodland owner survey.

Berger, A. L., Palik, B., D'Amato, A. W., Fraver, S., Bradford, J. B., Nislow, K., . . . Brooks, R. T. (2013). Ecological impacts of energy-wood harvests: Lessons from whole-tree harvesting and natural disturbance. *Journal of Forestry, 111*(2), 139-153.

Birdsey, R., Pregitzer, K., & Lucier, A. (2006). Forest carbon management in the united states. *Journal of Environmental Quality, 35*(4), 1461-1469.

Butler, B. J. (2006). Family forest owners of the united states, 2006. *Gen. Tech. Rep. NRS-27. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 72 p.,*

Carter, J. (2013). Export wood pellet facilities' raw material delivered cost trends. *Forest2Market: Market Watch,*

Chum, H., Faaij, A., Moreira, J., Berndes, G., Dhamija, P., Dong, H., . . . Mapako, M. (2011). Bioenergy IPCC special report on renewable energy sources and climate change mitigation ed O edenhofer et al.

Cooper, C. F. (1983). Carbon storage in managed forests. *Canadian Journal of Forest Research, 13*(1), 155-166.

Daigneault, A., Sohngen, B., & Sedjo, R. (2012). Economic approach to assess the forest carbon implications of biomass energy. *Environmental Science & Technology, 46*(11), 5664-5671.

Dewar, R. C. (1991). Analytical model of carbon storage in the trees, soils, and wood products of managed forests. *Tree Physiology, 8*(3), 239-258.

Dixon, R., Brown, S., Houghton, R. e. a., Solomon, A., Trexler, M., & Wisniewski, J. (1994). Carbon pools and flux of global forest ecosystems. *Science(Washington), 263*(5144), 185-189.

Earles, J. M., Yeh, S., & Skog, K. E. (2012). Timing of carbon emissions from global forest clearance. *Nature Climate Change, 2*(9), 682-685.

Fox, T. R., Jokela, E. J., & Allen, H. L. (2004). The evolution of pine plantation silviculture in the southern united states.

Galik, C. S., & Abt, R. C. (2012). The effect of assessment scale and metric selection on the greenhouse gas benefits of woody biomass. *Biomass and Bioenergy, 44*, 1-7.

Galik, C. S., Abt, R., & Wu, Y. (2009). Forest biomass supply in the southeastern united States—implications for industrial roundwood and bioenergy production. *Journal of Forestry, 107*(2), 69-77.

Hardie, I., Parks, P., Gottleib, P., & Wear, D. (2000). Responsiveness of rural and urban land uses to land rent determinants in the U.S. south. *Land Economics, 76*(4), 659-673. doi:10.2307/3146958

Heath, L. S., Nichols, M. C., Smith, J. E., & Mills, J. R. (2010). FORCARB2: An updated version of the US forest carbon budget model. *USDA Forest Service General Technical Report NRS-67.Northern Research Station, Newtown Square, PA,*

Helin, T., Sokka, L., Soimakallio, S., Pingoud, K., & Pajula, T. (2013). Approaches for inclusion of forest carbon cycle in life cycle assessment–a review. *GCB Bioenergy, 5*(5), 475-486.

Hicks Jr, R. R., Conner, W. H., Kellison, R. C., & Van Lear, D. (2004). Silviculture and management strategies applicable to southern hardwoods. *In: Gen.Tech.Rep.SRS 75.Asheville, NC: US Department of Agriculture, Forest Service, Southern Research Station.Chapter 7.p.51-62.,*

International Trade Administration Industry and Analysis Staff. (2016). *2016 top markets report renewable fuels sector snapshot: Biomass wood pellets.* (). International Trade Administration 2016 Top Markets Series: U.S. Department of Commerce.

Janowiak, M. K., & Webster, C. R. (2010). Promoting ecological sustainability in woody biomass harvesting. *Journal of Forestry, 108*(1), 16-23.

Johnson, E. (2009). Goodbye to carbon neutral: Getting biomass footprints right. *Environmental Impact Assessment Review, 29*(3), 165-168.

Jonker, J. G. G., Junginger, M., & Faaij, A. (2014). Carbon payback period and carbon offset parity point of wood pellet production in the South-eastern united states. *GCB Bioenergy, 6*(4), 371-389.

Katers, J. F., Snippen, A. J., & Puettmann, M. E. (2012). Life-cycle inventory of wood pellet manufacturing and utilization in wisconsin*. *Forest Products Journal, 62*(4), 289-295.

Lamers, P., & Junginger, M. (2013). The 'debt'is in the detail: A synthesis of recent temporal forest carbon analyses on woody biomass for energy. *Biofuels, Bioproducts and Biorefining, 7*(4), 373-385.

Lubowski, R. N., Plantinga, A. J., & Stavins, R. N. (2008). What drives land-use change in the united states? A national analysis of landowner decisions. *Land Economics, 84*(4), 529-550.

Magelli, F., Boucher, K., Bi, H. T., Melin, S., & Bonoli, A. (2009). An environmental impact assessment of exported wood pellets from canada to europe. *Biomass and Bioenergy, 33*(3), 434-441.

Marland, G., & Schlamadinger, B. (1995). Biomass fuels and forest-management strategies: How do we calculate the greenhouse-gas emissions benefits? *Energy, 20*(11), 1131-1140.

Matthews, R., Mortimer, N., Mackie, E., Hatto, C., Evans, A., Mwabonje, O., . . . Tubby, I. (2012). Carbon impacts of using biomass in bioenergy and other sectors: Forests. *Research Agency of the Forestry Commission, Rep.URN D, 12*

McKechnie, J., Colombo, S., Chen, J., Mabee, W., & MacLean, H. L. (2010). Forest bioenergy or forest carbon? assessing trade-offs in greenhouse gas mitigation with wood-based fuels. *Environmental Science & Technology, 45*(2), 789-795.

Miner, R. A., Abt, R. C., Bowyer, J. L., Buford, M. A., Malmsheimer, R. W., O'Laughlin, J., . . . Skog, K. E. (2014). Forest carbon accounting considerations in US bioenergy policy. *Journal of Forestry, 112*(6), 591-606.

Monthly densified biomass fuel report. (2016). ().U.S. Engergy Information Administration.

Moorhead, D. J., & Dangerfield, C. W. (1998). Intensive forest management: 1. shifting rowcrop and pasture land to tree crops in georgia: Marginal crop and pasture acres examined.*98*(048)

Nepal, P., Wear, D. N., & Skog, K. E. (2015). Net change in carbon emissions with increased wood energy use in the united states. *GCB Bioenergy, 7*(4), 820-835.

Newell, R. G., & Stavins, R. N. (2000). Climate change and forest sinks: Factors affecting the costs of carbon sequestration. *Journal of Environmental Economics and Management, 40*(3), 211-235.

Nickerson, C., Ebel, R., Borchers, A., & Carriazo, F. (2011). *Major uses of land in the united states, 2007* US Department of Agriculture, Economic Research Service.

Pan, Y., Birdsey, R. A., Fang, J., Houghton, R., Kauppi, P. E., Kurz, W. A., . . . Hayes, D. (2011). A large and persistent carbon sink in the world's forests. *Science (New York, N.Y.), 333*(6045), 988-993. doi:10.1126/science.1201609 [doi]

REGULATION (EC) No 443/2009 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL. (2009). *Official Journal of the European Union, 52* doi:10.3000/17252555.L_2009.140.eng

Sackett, J. (2014). *Southeast U.S. wood pellet plants exporting to europe*. **www.southernenvironment.org**: Southern Environmental Law Center.

Schlamadinger, B., & Marland, G. (1996). The role of forest and bioenergy strategies in the global carbon cycle. *Biomass and Bioenergy, 10*(5), 275-300.

Schlamadinger, B., Spitzer, J., Kohlmaier, G., & Lüdeke, M. (1995). Carbon balance of bioenergy from logging residues. *Biomass and Bioenergy, 8*(4), 221-234.

Searchinger, T. D., Hamburg, S. P., Melillo, J., Chameides, W., Havlik, P., Kammen, D. M., . . . Oppenheimer, M. (2009). Fixing a critical climate accounting error. *Science, 326*(5952), 527.

Sedjo, R., & Tian, X. (2012). Does wood bioenergy increase carbon stocks in forests? *Journal of Forestry, 110*(6), 304-311.

Smith, P., Davies, C. A., Ogle, S., Zanchi, G., Bellarby, J., Bird, N., . . . Cowie, A. (2012). Towards an integrated global framework to assess the impacts of land use and management change on soil carbon: Current capability and future vision. *Global Change Biology, 18*(7), 2089-2101.

Stephenson, A. L., & MacKay, D. J. (2014). Life cycle impacts of biomass electricity in 2020. *UK Department of Energy and Climate Change,* Walker, T., Cardellichio, P., Gunn, J. S., Saah, D. S., & Hagan, J. M. (2013). Carbon accounting for woody biomass from massachusetts (USA) managed forests: A framework for determining the temporal impacts of wood biomass energy on atmospheric greenhouse gas levels. *Journal of Sustainable Forestry, 32*(1-2), 130-158.

Zanchi, G., Pena, N., & Bird, N. (2012). Is woody bioenergy carbon neutral? A comparative assessment of emissions from consumption of woody bioenergy and fossil fuel. *GCB Bioenergy, 4*(6), 761-772.