ABSTRACT

WU, YUN. An Integrated Multi-Feedstock Modeling Approach towards Assessing Forest Resource Sustainability. (Under the direction of Dr. Robert C. Abt).

Increased utilization of forest resources for bioenergy production poses new challenges to decision making in terms of forest removal and management. In order to minimize the potential negative impacts from bioenergy production on forest resources, sustainability has been emphasized as the key. However, current literature does not address the question of regional forest resource sustainability in response to biofuel production. Dynamic and spatially detailed modeling efforts are strongly needed towards understanding the tradeoff between sustainability and biofuel related demand. The overall purpose of this study is to fill the literature gap by evaluating the changes in aspects of forest sustainability related with growing national biofuel production, while considering uncertainties in policy, market, and technology. This study contributes to the literature by solving the problem of modeling for competition among feedstocks for biofuel production, between fiber and biofuel for biomass, and also in quantifying the bioenergy related impacts on forest resource sustainability dynamically. Furthermore, policy implications on resource sustainability are also obtained by modeling for varying tax credit/subsidy inputs, biofuel demand patterns, and technology improvements.

The integrated modeling system involves mainly three models, an Agricultural Policy Simulation Model (POLYSYS), the Multi-Feedstock Model (MFM), and the Sub-Regional Timber Supply Model (SRTS). Both POLYSYS and SRTS have been used separately to examine the policy, whereas the MFM is developed in this study to link the other two models and reflect biofuel production/cost functions. In this way, forest resources can be more

realistically represented; the methodology also provides bioenergy policy implications in terms of resource sustainability.

The study's main results and conclusions include (1) softwood pulpwood inventory and price are more sensitive than other forest products to changes in biofuel production; (2) with a rise in biofuel production, the area of each forest land management type becomes larger than without biofuels but still decreasing; (3) the forest age class structure becomes more bimodal with biofuel production, potentially leading to a shortage in sawtimber supply in the future; (4) biofuel mandates, corn ethanol tax credit removal, and technology improvement in wood-based biofuels all promote a greater demand for woody biomass, but at different rates; (5) The logging residue removal rate needs to be about 50% to sufficiently meet bioenergy demand for pulpwood; (6) delaying meeting mandated biofuel targets to future years can improve maintaining a sustainable pulpwood forest inventory; (7) synergies might exist between using logging residues and pulpwood for biomass without causing severe consequences on the forest industry or the environment.

An Integrated Multi-Feedstock Modeling Approach towards Assessing Forest Resource Sustainability

by
Yun Wu

A dissertation submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy

Forestry

Raleigh, North Carolina

2011

APPROVED BY:

_____	_____
Robert C. Abt Committee Chair	Fred Cubbage
_____	_____
Barry K. Goodwin	Richard Phillips
_____	_____
Mark Downing	Gbadebo A. Oladosu

DEDICATION

To my beloved dad Wu Jing Cai and mom Deng Chun Fang

谨以此博士论文献给我亲爱的爸爸吴景才和妈妈邓纯芳

BIOGRAPHY

Yun Wu was born in a small city in the Northeast of China before her family moved to Sichuan Province, in the Southwest of China. She grew her love for the environment when she was very little. Seeing the rivers that she used to swim in turned into a filthy ditch, she decided to devote her life into protecting the environment, although she didn't understand what it would take or how far she could go at that time.

Difficult to study what you want at that time, she was admitted to the College of Engineering instead of the environment science that she selected as her first and only choice. She then spent four years to get her Bachelor's in Material Science and Engineering from Tianjin University and until now she still doubts if it was a waste of her time. During college, the yell from her heart was getting louder and louder, so she made up her mind to change. So she started sitting in environmental economics courses ever since junior year and preparing for the entrance test to the graduate school. Finally, after a great deal of efforts, she was successfully admitted with full scholarship to the school of Economics and Management in the same university, where she embarked on her career in environmental and natural resource economics. After graduation, Yun continued her passion in the Forestry Department of North Carolina State University. Also, she earned another Master in Statistics on route. However, her passion for solving environmental problems never ended there.

It is her goal to contribute to a better environment for the world. Thus, Yun takes advantage of every learning opportunity that helps to achieve it. Besides course work and projects at

school, she interned at different places all over the world, including Climate Change Policy Partnership at Duke University, Resources for the Future in Washington DC, Conservation International China Office, and the Young Scientist Summer Program at IIASA in Austria.

Currently, she works as a Research Associate in the Environmental Sciences Division at Oak Ridge National Laboratory. Her project mainly focuses on the biomass resource analysis in China, as part of the collaboration between DOE, USDA and the Chinese government. It has been a perfect job since she can actually do something for her own country to the environment solutions. In one word, Yun will continue to try to make a difference for the environment in developing countries.

ACKNOWLEDGMENTS

First of all, I'd like to pay special thanks to my advisor Dr. Robert C. Abt, who said "Enjoy your life" when we first met. Not until I came to the US, did I come to realize that school is just part of my life and I have been enjoying what I am working on. Thank you for teaching me something more important than getting high scores at school. I also want to thank my instructor Barry Goodwin, who always has faith in me and sees things from a bright side, when I almost lose my confidence. Also, I appreciate the help from my committee members Fred Cubbage and Richard Phillips in educating me of forest policy and biorefinery engineering.

I would also like to thank my previous supervisors and current colleagues at ORNL, Christopher Galik at CCPP, Roger Sedjo at RFF, Sylvain Leduc and Petr Havlik at IIASA, and Mark Downing, Bob Perlack and Debo at ORNL. I highly appreciate the opportunities working with you. Thank you for offering not only academic help but also sincere friendship. In particular, I am very grateful for Debo for his extraordinary patience and guidance on me through GAMS coding. Also, my special gratitude is paid to my colleague Matthew Langholtz, who did all the editing work for my dissertation. You are an excellent editor and awesome friend.

The funding of my PhD program comes from the Department of Forestry and Environmental Resources in North Carolina State University, Professor Robert Abt, and Environmental

Sciences Division of Oak Ridge National Laboratory. Without your financial support, I could never have finished my PhD program. Thank you!

Life would be boring without friends. I am very grateful for having good friends during my PhD program. I want to thank them for their time with me. Thank you, Jessica, Hayley, Simone, Sherry, Miao, Congnan, Na, Damian, Kevin,…and also my friends in Tennessee, Rocio, Maria, Xiwen, Ju Tong…The list can go much longer than the main body of my dissertation. I just want to say, thank you for entering my life and being my friends. No matter how far we are from each other physically, we are close in our hearts and we will always be. And I believe we will get together very soon.

In the end, I want to thank my parents, who spent most of their money on my education, who even hesitated at buying a new pair of socks when theirs were worn out, who were tough or even cruel sometimes on me just like the tiger moms described in Amy Chua's book, and who have been living alone by themselves in Sichuan province for the past 12 years since I left for college in 1999. Thank you!!! Hope I've lived up to your expectations.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1 INTRODUCTION

The beginning of the 21st century was marked by unconstrained promotion and advocacy of bioenergy production and bioenergy industries, primarily in corn-based bioenergy. Bioenergy was assumed to be a closed loop production, re-absorbing in growth the greenhouse gases emitted in fuel combustion. Bioenergy, especially biofuel, was therefore considered as panacea for climate change along with many other advantages, such as energy security and increasing farmers' income. However, bioenergy's carbon neutral assumption has recently been called into question; it has even been shown to potentially produce a carbon debt (Searchinger et al., 2008; Fargione, Hill, Tilman, Polasky, & Hawthorne, 2008). Subsequently, there has been very active and comprehensive research in many aspects of bioenergy, covering an exhaustive range of topics from socioeconomics and environment to ecology and highlighting food/fuel/feed competition (Von Braun et al., 2008), GHG emission (Searchinger et al., 2008; Fargione, Hill, Tilman, Polasky, & Hawthorne, 2008), habitat/biodiversity loss (Mooney & Hobbs, 2000), land-use change (de Fraiture, Giordano, & Liao, 2008;Treguer & Sourie, 2006), rural income development (Peskett, Slater, Stevens, & Dufey, 2007), energy security (Elobeid & Tokgöz, 2006), technology readiness, policy efficacy (Tyner, 2007; Hertel, Tyner, & Birur, 2010), and so on. It is widely acknowledged that there have been some unintended consequences associated with the first-generation biofuels without any constraints. In order to avoid them, policy makers (EPA, 2005; EPA, 2007; EPA, 2010) have directed bioenergy production from food/feed biomass to

agricultural and forest residues, and more advanced biomass, such as energy crops grown on marginally profitable cropland and pastureland. Thus, second-generation and more advanced bioenergy has received a great deal of attention for its many advantages over corn-based bioenergy. Nevertheless, a portion of the scientific community remains concerned about the potential loss in environmental services due to second-generation biofuels, especially forest-based biofuels, such as biodiversity loss, land-use change, and competition with fiber/livestock supply. Careful analysis of forest-based biofuel is necessary to better understand the ecological and economic implications. Thus, in order to avoid the previously mentioned unintended consequences, policy makers and scientists have proceeded with caution in promoting its production.

Nonetheless, there is strong belief that bioenergy can contribute to the abatement of GHG emissions and enhancing ecologies depending on how the bioenergy system is designed and practiced. As is being realized by more and more researchers, sustainable production is the key. Bioenergy has the potential to mitigate GHG emissions, land-use change, biodiversity loss, and some other climate change related issues. Possible negative impacts from biofuels can be minimized under a sustainable forest management and utilization scheme. Furthermore, Solomon (2010) has pointed out that cellulosic ethanol is the only ethanol that has potential to "be produced and consumed on a sustainable basis," among all currently and foreseeable commercial biofuels. Dale et al. (2010) also stated that the objective of sustainable bioenergy production is to enhance socioeconomic and ecologic benefits through quantitative analysis of environmental tradeoffs at different scales.

Looking through the literature, it becomes clear that the impacts of biofuel development on aspects of agricultural crop sustainability have been studied in great detail, as previously mentioned, but the sustainability of forest resources has not been considered as much. The questions still remain: how do forest resources respond to biofuel production, and what are the impacts on forest sustainability? Some studies try to solve this question, such as modeling efforts on the partial equilibrium models, the Forest and Agricultural Sector Optimization Model (FASOM) (McCarl et al. at Texas A&M University), the National Energy Modeling System (NEMS) (Energy Information Administration), and the Global Trade Analysis Project model (GTAP) (Center for Global Trade Analysis at Purdue University), but they do not provide information on the economic implications of competition with existing forest industry or enough spatial detail. The existing literature regarding these questions is reviewed in detail in the following chapter.

There are various criterion and indicator systems to evaluate forest resource sustainability, such as the Canadian Council of Forest Ministers, the International Forest Stewardship Council initiative, the National Sustainable Forestry Initiative, and so on. In general, they include aspects of biological diversity, forest ecosystem productivity, health and vitality, soil and water resources, carbon cycles, socio-economic benefits, and forest related legal, institutional and economic frameworks. Among all of them, forest product inventory, removal, and price are widely used for assessing the economics of forest industry, and indicators such as forest land area and management type, age class structure, logging residue utilization rate, etc. can be adopted to evaluate ecological aspects of forest

sustainability. In addition, they shed some light on other sustainability criteria and indicators, such as forest non-market values, water resources, nutrient/organics maintenance, and wildlife habitat.

This study aims to explore the biofuel development impacts on the aspects of regional forest resource sustainability, which includes forest product inventory, removal, price, logging residue, forest land management, and age class. Also, it is notable that future uncertainties in biofuels policy, market, and technology present great challenges for policy makers, land owners, and investors. Thus, these aspects are examined here under various policy and technology scenarios, including biofuel mandates, tax credit removal, technology improvement, and biofuel production schedule. The analysis does not try to optimize the overall socioeconomic and ecologic benefits associated with sustainable bioenergy development. Rather, it evaluates the tradeoff between bioenergy development and forest resource sustainability perspectives for policy makers.

The dissertation body is comprised of five sections: introduction, literature review, methodology, results, and conclusions and discussions. Section 2 is organized by reviews on different types of feedstocks, especially forest biomass, bioenergy-related policies, and two model systems for bioenergy policy assessment, followed by the purpose of the present study. A methodology is proposed in Section 3 to provide a dynamic link between biofuel development and forest resource sustainability. Then in Section 4 the results are summarized, and the last section presents conclusions obtained from the results and a discussion of the findings' implications.

2 LITERATURE REVIEW

2.1 Reviews on Biomass

Biomass includes all plant and plant-derived matter, and is found in agricultural crops and trees, wood and wood residues, plants (including aquatic plants), grasses, municipal residues, and other residue materials (R. D. Perlack et al., 2005). Biomass can be converted to energy or to alternative fuels, can be combusted alone or co-fired with another fuel such as coal or natural gas, and can be substituted for petroleum products in the production of industrial oil and organic chemicals.

A large variety of biomass feedstocks are currently available for producing biofuel. The biomass resource base includes a wide range of primary resources and secondary and tertiary residues, which are categorized by Perlack et al. (2005). Forest primary biomass resources include residues generated from the collection of roundwood/fuelwood, as well as from land management activities and fuel wood collection and use, while agricultural primary biomass is composed of crop residues from major crops, grains used for biofuel, perennial grasses and woody crops. Secondary biomass resources include residues from the production of primary biomass and animal manures, and food/feed processing residues. Tertiary biomass resources include urban wood residues, municipal solid waste (MSW) and post-consumer residues, and landfill gases.

Biofuels may be categorized as first-, second-, and third-generation biofuels. Their associated biomass is sometimes identified as first, second, and third generation feedstocks. First-generation biofuels are mainly produced from agricultural crops that are used for

food/feed production, such as corn, sugar cane, oilseeds, wheat, etc. Second-generation biofuels, considered advanced biofuel, are produced from non-food feedstock, including corn stover, wheat straw, woody biomass, and energy crops. However, the conversion technology has not been commercialized at this time. More advanced biofuels, such as algae and bio-propanol or bio-butanol, are known as third-generation biofuels.

The world ethanol production has sharply increased in the first decades of 21th century from 299 thousand barrels per day in 2000 to more than 1.3 million barrels per day in 2009 (Energy Information Administration, 2011). Meanwhile, biodiesel grows at an even higher rate, from around 21 thousand barrels per day in 2001 to more than 308 thousand barrels per day in 2009 (Energy Information Administration, 2011). Further, biofuels production is projected to grow.

Bio-ethanol and biodiesel are mostly used for transport fuels by blending into gasoline at different mixes. In the US, E10, with 10% ethanol blended in gasoline, is the most common, and currently blenders are allowed to mix up to 15% ethanol. The deployment of E15 is faced with the same infrastructure challenges as E85.

The US has become the world's leading ethanol producer since 2006 with more than 318 thousand barrels per day, representing more than half of global production (Energy Information Administration, 2011). One might wonder if feedstock resources in the US can support such a big industry. To answer this question, a group of scientists at Oak Ridge National Laboratory assessed the resource availability in the US and published the "Billion Ton Report." It concludes that the biomass in the US could provide 1.3 billion tons each year

from agricultural and forest resources, and supply biomass for sufficient biofuel production to replace at least 30% of the petroleum consumption in the US. This result has been updated to include perennial plants and sustainability constraints in the forthcoming Billion-Ton Study report (B. Perlack et al., 2011). What remains to be seen, however, is the impact that increased use of biomass for energy and biofuels will have on the same resource's continued availability for other uses, such as food, feed, and fiber.

2.1.1 Corn-based Feedstock

First-generation biofuel, produced from grain-based biomass using conventional technology, is very controversial. Searchinger et al. (2008) were the first to provide an account of the carbon emissions of corn ethanol due to land-use change. They noted that it would take 167 yrs for corn ethanol to overcome the carbon debt it incurs from land-use change, and that switchgrass could provide carbon savings within four decades. Fargione et al. (2008) showed that the increased carbon emissions from land-use change resulting from food-crop biofuel production are many times larger than the carbon savings of first-generation biofuels. Also, Mooney and Hobbs (2000) estimated that the biodiversity loss from first-generation biofuel production could be costly at present. Soil erosion, nutrient depletion, and fertilizer use can be related to biofuel production, as shown by Hill et al. (2007). Furthermore, as biofuel production accelerates, the additional water required to irrigate fast growing crops has implications on total water availability and quality (de Fraiture et al. 2008)(de Fraiture et al. 2008). While biofuels is promoted in order to reduce

GHG emission, other non-GHG emissions and air pollution has raised public health concerns, as is noted in several studies(Mapemba, Epplin, & Huhnke, ; McCormick & Golden, 2005) .

Economically, first-generation biofuel production is blamed for competing with food and feed markets, and there have been efforts (Von Braun et al., 2008; Rosegrant, 2008;Banse, Tabeau, Woltjer, & van Meijl, 2007; Schmidhuber & Tubiello, 2007) to evaluate the relationship between biofuel production and a rise in food prices, although the results are controversial. Also, since biofuel production has the potential to cause deforestation and habitat/biodiversity loss, several studies have proposed different quantitative models. They tried to predict land-use change as a result of biofuel production and thereby the environmental costs/benefits of biofuels. It was concluded that biofuel production has the advantages of increasing farmers' incomes and improving domestic energy supply, besides reducing GHG emission. However, after a close look at the farmers' incomes in several studies, the impacts of a massive development of biofuel on farmers' incomes and on jobs remain quite modest (Treguer & Sourie, 2006), and the potential impact on poverty reduction can be large but very fragile (Peskett et al., 2007).

2.1.2 Forest and other advanced biomass

An important source of second generation biomass, native perennial plants, has already been shown to aid in preserving wildlife habitat and soil nutrients, and they are also less expensive to manage than corn. In addition, they can be planted around annual crops as a

buffer zone to help prevent soil erosion. However, greater economic incentives are required to initiate large-scale planting of perennial plants. Plus the planting of grass can be land intensive. Thus, careful farming practice guidelines should be followed so as not to displace land that is used for food or fiber production.

Forest biomass can be used to produce bioenergy, such as electricity and biofuels. The focus of production has been shift from crop-based ethanol production to other more advanced biofuels, evidently from the mandates in the US Energy Independence and Security Act of 2007. Ever since, there have been research and development efforts and funding invested into the development of second generation bioenergy, including forest-based biofuel. The conversion technology has not been applied commercially, but demonstration plants exist.

In some areas of the country, like the Southeastern United States, forest biomass is a prime source of feedstock for three inter-related commodities: wood and paper products, bioenergy, and biofuels. If one assumes that the availability of forest biomass is limited by forest growth rates and the total land available for forest cultivation, an increased use of forest biomass for any one of these commodities may come at the expense of the supply available for the others. This competition between end-uses may necessitate decisions to be made about future land-use and management strategies.

The use of forest biomass as a source of energy has a number of advantages over traditional fossil fuels. Forest biomass resources are renewable over moderate to long time periods. The combustion of forest biomass in place of fossil fuels can result in reduced

sulfur and mercury emissions. Even when co-fired, or used as a supplement to fossil fuels such as coal, the use of forest biomass can significantly reduce facility CO_2 and NO_x emissions (Haq, 2002; Mann & Spath, 2001). There is no universally accepted number for the carbon emission reduction of each biofuel. Findings vary based on methodology, data, assumptions, scale and level. However, the consensus is that first-generation biofuel can reach a 20% carbon emission reduction following recommended management practice, while cellulosic and more advanced biofuel can reach more than 50% and 60% reduction, respectively, as required by Renewable Fuel Standards 2007 (RFS2) on minimal emission reduction.

Forest biomass supply varies greatly by region. The variety is particularly important given the strong role that transportation costs play in the delivered price of biomass. Forest biomass can only be considered a viable feedstock if it can be sourced near the point of processing or end-use.

The US Forest Service's "Forest Resources of the United States 2007" (Smith, 2009), published in 2009, presents a comprehensive overview of the Nation's forests. Of all the nation's forests, about two-thirds (514 million acres) was classified as timberland, the land that is able to produce 20 cubic feet per acre per year of industrial wood. Timberland is estimated to have one trillion cubic feet of timber, 93% of which is in growing stock. However, timber harvests have been declining since the early 1990s, while the extra demand is filled up by foreign imports. A total of 15 billion cubic feet of timber is harvested for

industrial products and fuelwoods. Among the 15 billion, almost 87% came from growing stock sources and the rest from non-growing stock.

The South, with 9.7 billion cubic feet, accounted for 62% of the Nation's total growing-stock removal in 2007. Softwood removal rates were 5.5% of the softwood growing stock inventory, and hardwood removal rates were 1.2% of its growing stock removal in the south regions. Between 1998 and 2004, the southern timber market experienced a so-called "adjustment period" following 12 years of rapid growth (Wear, Carter, & Prestemon, 2007). This period was characterized by a decline in demand, especially for pulpwood and softwood sawtimber.

Logging residues are available in large quantities and can be recovered from commercial harvest and land clearing operations. In 2007, more than 4.5 billion cubic feet of logging residue was produced and left in the forest, of which 28% was from growing stock and the rest from non-growing stock. Due to a higher utilization of softwood trees, they amounted to 78% of total product output but only 50% of total logging residues. Mill residues, on the other hand, are used to produce wood products, bio-energy, energy products and other miscellaneous products. Very little mill residue (1.5% during 2007) is not utilized.

As has been known for years, forest resources can be used to produce bioenergy to reduce Greenhouse Gases (GHG) emissions that could otherwise be released from fossil fuels. Also, forest resources can be used as a cost-effective carbon reservoir for atmospheric carbon sequestration. Carbon emission is the product of changes in acres and carbon stock. Land-use change and related emissions reductions have been emphasized as a key factor in abating

climate change in literature, but adequate attention is not given in current literature to carbon stock change. The change in carbon stock plays an important role in determining carbon emissions from land-use change. Specifically, the carbon stock within an existing forest depends on the inventory (as a result of growth, harvest and land-use change), soil type, and forest profile, such as age class, species, management type, and so on.

Cellulosic biofuel can be produced from forests, energy crops and even as byproduct from the forest industry. The expansion of cellulosic biofuel has a vast impact on all economy sectors and the environment. As Dicks et al. (2009) state, there is great need for the development of a cellulosic biofuel industry in the U.S. South and the identification of the size and locations of cellulosic bioenergy plants, which have a wide impact on local economies. Nonetheless, the development of the feedstock market and cellulosic biofuel market are described as a "chicken and the egg" problem in some studies in the same report. The establishment of one market is the incentive for the other. The switch to cellulosic biofuel might take many years, and when the switch will happen remains in question.

2.1.3 Sustainability

In general, sustainability is accepted as a concept that implies a non-declining overall welfare over generations. The commonly adopted Criterion and Indicators (C&I) and certification schemes by many countries include three aspects: environmental, social and economic. Overall sustainability is determined by the integration of sustainability in terms of these three aspects, but in empirical analysis, the indicators are assessed separately due to the

complexity of integration. Solomon (2010) reviewed sustainable biofuel criteria and certification systems. The Roundtable on Sustainable Biofuels has made practical efforts towards establishing a set of international principles and criteria. The International Organization for Standards is also developing international standards for biofuels.

Sustainability can contribute significantly to solving some of the issues associated with bioenergy production and climate change. The ultimate goal of conducting sustainable production is to optimize the overall ecological and socio-economic benefits through quantitative tradeoffs between socio-economic, ecological, and environmental indicators. Many scientists have warned that forest harvesting must follow sustainability C&I and certification schemes, in order to avoid negative consequences such as those observed in corn-based biofuel production. Some of the researchers (Fritsche et al., 2010) have proposed strategies towards more efficient and sustainable biomass production and utilization, including (1) Increasing biomass yield and productivity; (2) Conducting sustainable management practice on farms and forests; (3) Prioritizing degraded/unused land and waste/residue biomass use; (4) Promoting biomass for heat and power; (5) Increasing biomass/bioenergy efficiency in transport, industry and households, and so on.

In particular, for sustainable forest management in the US and the world, there are different C&I systems and certification schemes already available, such as the Helsinki Process for European countries, the Montreal Process for most of the temperate forest countries, and the national level indicator systems such as the Canadian Council of Forest Ministers C&I framework. Generally, forest sustainability includes biological diversity,

forest ecosystem productivity, health and vitality, soil and water resources, carbon cycles, socio-economic benefits, and forest-related legal, institutional and economic frameworks.

Existing certification systems include the international Forest Stewardship Council Initiative, the Sustainable Forestry Initiative (SFI), and the Canadian Standards Association systems (Adamowicz & Adamowicz, 2003). However, when dealing with the multi-faceted sustainable forest-based biofuel, there should be more C&I and certification schemes at multiple levels involved or proposed, mandatory or voluntary. Dargusch et al. (2010) categorized the certification schemes into four groups: (1) forest stewardship and sustainable supply chain, (2) bioenergy produced from woody biomass, (3) forest-based greenhouse gas emissions offsets and carbon markets, and (4) forest ecosystem services.

2.2 Bioenergy Policies in the US and the World

Internationally, there are three topical policy proposals related to carbon emissions (Sandén & Azar, 2005):

1. Carbon trading in the Kyoto protocol
2. Green certificates and renewable energy portfolios
3. Bioenergy directives

As pointed out by Sanden (2005), carbon trading in the Kyoto protocol is very contentious. The US argues for the unconstrained use of flexible mechanisms, and the argument is supported by most economists due to cost-efficiency. The problem is that the diffusion of green technologies would be slowed due to the relatively high costs in their early

stages. However, the EU is in favor of a stringent target because of the larger incentives to develop new technologies to lower abatement costs. Also, according to the study by Oates et al. (1989), the cost from command and control policy instruments can be comparable with tradable permits if designed properly.

Green certificates and renewable energy portfolios aim to increase the use of green technologies by mandating their adoption. Such an approach allows for the flexibility of choosing different renewable resources based on their specific conditions. In the US, some states have started to implement the Renewable Portfolio Standards which require a minimal proportion of energy being produced from renewable sources. Nevertheless, some technologies, such as solar cells, onshore and offshore wind, etc. are too costly to be competitive with other technologies.

Bioenergy directives have become common all over the world. The Energy Act (2007) in the US requires a minimal level for different types of biofuel production. In China, the Medium and Long-term Development Plan for Renewable Energy (2007) calls for the renewable energy proportion to increase to 10% of national energy consumption by 2010 and 15% by 2020. A range of renewable energy targets would likely be needed to meet these targets.

As a low- or zero-carbon substitute for fossil fuels, biofuel has the potential to reduce GHG emissions, increase farmers' incomes, improve energy security, and help stabilize energy prices. However, biofuel development has raised controversies. Both studies by Searchinger et al. (2008) and Fargione et al. (2008) showed that food-crops based ethanol

produced more carbon emissions after accounting for the effects of land-use change. Also, several studies(Mooney & Hobbs, 2000;de Fraiture et al., 2008; Peskett et al., 2007; Elobeid & Tokgoz, 2006)have shown biofuel and biofuel policy impacts on habitat/biodiversity loss, soil erosion, nutrient depletion, water availability and quality, livestock, labor incomes, international trade and energy security, as previously mentioned.

Ethanol has been subsidized since as early as 1978 by the Energy Tax Act of 1978, which provided an exemption to the 40 cents/gallon federal fuel excise tax on gasoline for fuel blended with at least 10 percent ethanol, as a response to the petroleum shortage. This tax exemption was increased to $0.60/gallon by the Tax Reform Act of 1984 and then, in 1998, the Transportation Equity Act of the 21st Century reduced it to $0.51/gallon. Subsequently, this excise tax exemption was changed into an ethanol blender tax credit and extended to 2010 in the American Jobs Creation Act of 2004. The American Jobs Creation Act modified the small ethanol producer tax credit by allowing the $1.5 million credit to be passed to farm owners of ethanol cooperatives.

The US Energy Independence and Security Act signed in 2005 (EPA, 2005) established the Renewable Fuel Standards (RFS1) to mandate biofuel production from 4 billion gallons in 2007 to 7.5 billion in 2012. In addition, it amended the definition of a "small ethanol producer" from 30 mgy of ethanol production to 60 mgy of ethanol production, and approved tax credit for E85 infrastructure.

Besides the blended federal credit subsidies described above, there have been other federal and state subsidies. In December 2007, the US Energy Independence and Security

Act of 2007 was signed into law. It requires American "fuel producers to use at least 36 billion gallons of biofuel in 2022" (EPA, 2007; EPA, 2007) . Of the total amount of biofuels produced, 21 billion gallons is required to be obtained from cellulosic ethanol and other advanced biofuels. The law promotes the adoption of biofuel and advanced biofuel producing technologies. This Act significantly increased the biofuel production from 9.0 billion gallons in 2008, which was required by EISA RFS1 2005, to 36 billion gallons by 2022. Ever since the change in Renewable Fuel Standards, there has been widespread debate over its effects on various sectors both in the US and internationally.

Table 1 EISA RFS2 Requirements on Biofuel Volume (unit: billion gallons)

year	RFS total	Corn ethanol	Cellulosic	Total advanced
2007				
2007				
2008	9	9		
2009	11.1	10.5	0.5	0.6
2010	12.95	12	0.1	0.95
2011	13.95	12.6	0.25	1.35
2012	15.2	13.2	0.5	2
2013	16.55	13.8	1	2.75
2014	18.15	14.4	1.75	3.75
2015	20.5	15	3	5.5
2016	22.25	15	4.25	7.25
2017	24	15	5.5	9
2018	26	15	7	11
2019	28	15	8.5	13
2020	30	15	10.5	15
2021	33	15	13.5	18
2022	36	15	16	21

On May 26, 2009, the EPA released a Notice of Proposed Rulemaking (NPRM) to deal with the change in RFS. It proposed a methodology to estimate fuel lifecycle emissions

associated with both direct and indirect land-use change resulting from producing renewable fuels. The NPRM proposed to use two models to estimate both types of land-use change and their resulting emissions. The proposal went under peer review over the methodology, including the models, emission factors and data. To reflect the review comments, the EPA made various changes in the final rule issued on Feb 3, 2010. After these modifications, most types of biofuels studied have lower emission estimates, some of which are dramatic reductions. This is largely due to lower emissions from international land-use change. As recognized by some researchers, the lower land-use change impact is mainly attributed to three changes in the estimation: (1) higher crop yields, (2) higher co-product efficiency, and (3) better satellite/imagery data. Also, the GTAP model is used to test the results from the NPRM's estimation models.

Table 2 Land-use change Models Proposed by NPRM (Saundry, 2009)

Key Issue	Domestic Agriculture	International Agriculture
Amount, or area, of land converted	FASOM (domestic agricultural sector model)	CARD/FAPRI (international agricultural sector model)
Location of land-use changes	FASOM (regional-level)	CARD/FAPRI (country level)
Land types, or biomass converted	FASOM (modeled interactions with cropland, pasture, CRP and forest)	MODIS Satellite Data (recent trends of land conversion between different land types)
GHG emissions from land conversion	FASOM (e.g. DAYCENT for soil carbon changes)	Winrock/IPCC

Source: USDA Agricultural Air Quality Task Force May 2009 Meeting. Adapted by CRS.

On June 30, 2010, the EPA withdrew several amendments made to the RFS2 regulations issued earlier on May 10, 2001. Subsequently, on Dec 21, 2010, the EPA

published the Regulation of Fuels and Fuel Additives: Changes to Renewable Fuel Standard Program; Final Rule on its website (EPA, 2010). This final rule takes effect on January 1, 2011.

Finalized on Jan 12, 2009, the California Low Carbon Fuel Standard (LCFS) requires a 10% reduction in carbon intensity from the baseline fuels by 2020. Instead of imposing biofuel mandates or total emission reduction, it regulates the average lifecycle emission per unit of energy for transportation fuels to be 10% below gasoline and diesel fuel. It is entirely performance based and flexible enough for different parties to choose their optimal fuel mix. Contrary to EISA, LCFS does not exempt current biofuel producers.

The 111th Congress plays a role in overseeing the EPA on implementing and amending RFS2, as well as integrating it into other regulations.

Furthermore, the policies that promote forest-based biofuel production include the Biomass Research and Development Act of 2000, the 2002 Farm Bill, the 2005 Energy Policy Act, the 2007 Energy Independence Security Act, the Healthy Forests Restoration Act of 2003, and the Food, Conservation, and Energy Act of 2008.

2.3 Partial Equilibrium and Computable General Equilibrium

Partial equilibrium (PE) models and computable general equilibrium (CGE) models have been employed to estimate biofuel policy impacts nationally and internationally, especially in terms of land-use change. Both of the two model systems have their own

advantages and disadvantages, and the choice of which model to use depends on the policy scope, time horizon, and geographic scope of the problem.

Partial equilibrium models, such as FASOM, the Food and Agricultural Policy Research Institute's Model (FAPRI), NEMS, and the Policy Analysis System (POLYSYS), have a higher degree of disaggregation and thereby require a higher resolution dataset. FASOM is a dynamic, partial equilibrium model that optimizes the total welfare of the agricultural and forestry sectors in the US. The updated version FASOM-GHG v2 has included an expanded sector to model more than a dozen feedstocks. The current agricultural market information is also added; so are timberland stocks, distribution of land ownership and harvest schedules (Beach, Daigneault, McCarl, & Rose, 2010). However, FASOM-GHG v2 does not provide regional information on land use changes or their impacts on the landscape and carbon stock.

FAPRI is used to project the impacts of a policy change on agricultural activities across 35 countries and regions and over 13 crops and 2 livestock categories. It models the trade of agricultural commodities and the demand for agricultural land instead of land market directly. The FAPRI model system becomes a "CARD" model when it is used at the Center for Agricultural and Rural Development (CARD). CARD is a partial equilibrium modeling system and is made up of supply and demand and cross-commodity interactions for important agricultural products. The model estimates agricultural development on a year-by-year projection for all of the important countries for given commodities (Baker, Hayes, & Babcock, 2008; Elobeid & Tokgoz, 2006; Tokgoz et al., 2007).

Searchinger et al. (2008), using the FAPRI model, assume that projected yield improvements would be offset by the lower productivity of the additional lands converted for crop/corn production, so the yield improvement can be considered negligible by the model. Intuitively, a constant yield assumption would make indirect land-use changes unavoidable, which explains to a large degree the large indirect land use change (ILUC) emission in the result. However, FAPRI is heavily dependent on the yield improvement, so a change in the assumption of yield response can change the result remarkably. It is critical to examine the validity of this assumption. Also, Searchinger et al.'s (2008) assumed initial and ending volumes of ethanol productions are too high compared to the volume required by RFS2.

There have been a series of criticisms (Darlington, 2009; Mathews & Tan, 2009) of Searchinger et al.'s (2008) paper. They have pointed out that Searchinger et al. and the FAPRI ignore a range of important aspects, including the direct planting of crops for bioenergy, other types of low-carbon biofuels, trade between countries, and, most importantly, the exogenous yield improvement. The study's carbon emission data was taken from Woods Hole Research Center recorded in the 1990s, which overestimated the emission compared to the emission projection constructed by the Intergovernmental Panel on Climate Change (IPCC).

Moreover, Hayes et al. (2009) projected the impacts of RFS in a modified FAPRI model where a combination of RFS and energy prices set up a price floor for corn ethanol in long-run equilibrium. This model assumes that no deforestation resulted from the biofuel expansion in the US and that the expanded cropland comes from CRP or grassland. A

baseline scenario is set up by using results from US and international commodity models from January of 2008. The model is extended to project to the year 2022, so the long-run equilibrium is studied rather than immediate impacts. Also, it endogenizes gasoline prices relative to crude oil prices, natural gas prices and farm-level variable costs. Thus a two-way link between US ethanol and gasoline sectors is included (the endogenous gasoline price) (Du & Hayes, 2008). By doing so, the FAPRI model is trying to fix the disadvantages of partial equilibrium models, which do not perform well when dealing with long-term impact projections and changes in relative prices (Van der Werf & Peterson, 2009).

The National Energy Modeling System (NEMS) (Energy Information Administration (EIA), 2009) was developed by the Department of Energy to forecast energy market information for energy policy makers. In the Petroleum Market and Renewable Fuels modules, biomass prices are derived from supply curves which are based on the accessibility of resources to the electricity or biofuel sector. The biomass feedstock considered by the model includes urban wood waste and mill residues, forest residues, energy crops, and agricultural residues. Then these feedstock costs are added to other operating costs for the modules. The modified NEMS model GT-NEMS takes into consideration three energy and climate policies: Renewable Fuel Standards, Renewable Electricity Standards, and national policy of carbon constraints. However, neither of them is designed to examine competition with existing food/feed/fiber industries or related resource sustainability implications.

POLYSYS is an agricultural policy simulation model and has been used to examine bioenergy policy implications. It optimizes feedstock allocation through interactions of

feedstock sources among their respective modules, including a county-level crop supply module, national crop demand module, national livestock module, agricultural income, and a newly added forest module. However, the forest module in POLYSYS is treated independently from any other modules. There are no interactions between forest and agriculture in the model.

In addition, it is notable that a newly published article by Ince et al. (2011) models the impacts of expansion of domestic wood energy consumption on the US forest sector under hypothetical wood-based energy policy scenarios. It applies the US Forest Products Module (USFPM) within the Global Forest Products Model (GFPM) and comes to the conclusion that the energy consumption expansion can be supplied by logging residues that are currently unutilized and also mill residues in most scenarios. However, it does not look at aspects of sustainability due to the expansion of wood energy consumption. Also it warns possible divergence when the forest sector is examined at a sub-regional level.

All the PE models have their own advantages when applied to detailed datasets of specific regions' biophysical characteristics, thus making predictions more realistic. However, they do not perform as well when it comes to national or international policies, which affect relative prices, land-use change decisions, and international feedbacks (Van der Werf & Peterson, 2009).

On the other hand, the CGE model is generally used to analyze the effects of biofuel policy on all sectors of the economy. However, CGE models have long been criticized for their inability to model dynamics or exogenous yield improvement (Air Improvement

Resource, 2009; Darlington, 2009; Sheehan, 2009). So a CGE is not able to deal with dynamic yield improvement in agricultural crops and energy crops, or future population and food demand. The yield improvement in response to crop prices and energy prices are included in different models, but the exogenous yield improvement induced by exogenous factors such as technology progress or weather change remains left out. As warned by Palatnik et al. (2009), CGE models such as GTAP assume a non-linear production for land as an input, and this requires a monetary quantification of land values instead of physical units. It complicates a straightforward interpretation of land-use change. In addition, assumptions about land production and transformation structures and elasticities call for strict validation, given their crucial influences on model estimation.

In contrast to estimating forestland converted into cropland in GTAP, CARD/FAPRI models do not yet estimate land conversion from forest. The lack of consideration can be justified by the lack of evidence of forestland converted to agricultural land due to the increased biofuel demand over the past three years. Instead, the increase in cropland is a result of "a reduction in CRP acres and … increased double cropping of soybeans after wheat" (Babcock, 2009). Also, Babcock et al. point out that, due to a lack of reliable data about foreign countries, the accuracy of data on land-use change outside of the US is very limited. The CARB and EPA agree that the policy-induced biofuel expansion contributes to deforestation in the Amazon. But since there are many other causes of deforestation in Amazon, it is hard to say whether or how much deforestation is caused by ethanol expansion in the US. The science on indirect land-use change is still in its infancy.

In order to fix the disadvantages of PE and CGE models, there have been many efforts to augment CGE models internally or combining them with PE models externally. We have seen examples of model extension with GTAP, which has been upgraded over the years to include new structures or more details.

A good example of CGE internal extension is the GTAP-AEZ model, which links land-use change by agro-ecological zones for each region with the CGE model to estimate policy impacts. It includes land as a primary input in all production modeling. It modifies the GTAP model to better estimate land use transition. However, it only has one class for forest type, and it does not include biofuel sector. So it has to be further expanded before being applied to bioenergy policy evaluation.

There also have been several efforts to combine the strength of both PE and CGE models, or the PE and PE model, which becomes the integrated modeling system. Such models are based on the framework of CGE or PE and extended to include extra information and constraints. For example, KLUM (Ronneberger, Berrittella, Bosello, & Tol, 2009), a global land-use change PE model that predicts land allocation decisions, has been integrated with GTAP to study the environmental impacts of bioenergy policies. The method undertaken by KLUM is to differentiate between land classes, given the different characteristics in a specific land class. The introduction of biophysical aspects of land use decisions into GTAP considers the heterogeneity in land use and thus makes land-use change modeling more elaborate, flexible, and thus realistic. However, the difficulty lies in the technical problems including convergence and joint baseline selection. In a nutshell,

integrated assessment models link ecosystem/biophysical models with an econometric model. The econometric model provides options for decision making, and the decision is made through the dynamic model with a biophysical/ecosystem aspect and then sent back to the econometric model. Such an approach can take advantage of the strength from both PE and CGE models to better evaluate policy impacts when coupling PE with CGE models. However, these blended approaches raise technical challenges for computing power and data processing.

In order to address the above-described inability to capture forestry dynamics, GTAP tries to integrate the Global Timber Model (GTM) (B. Sohngen, Mendelsohn, & Sedjo, 2001) to "establish a future price path for forest products" (B. Sohngen, Golub, & Hertel, 2009; B. Sohngen, Tennity, Hnytka, & Meeusen, 2009). The recursive dynamic GTAP-Dyn (Ianchovichina & McDougall, 2001) is linked with the forward-looking forestry model GTM. It also accommodates the forest management adjustment to carbon price policies. Unmanaged forest land is included in the model, but the woody biomass still remains unconsidered since GTAP only regards pasture and idle land as possible land for cellulosic biofuel. However, GTAP does not include forest biomass as biofuel feedstock, yet. Nor does it differentiate between types of forest biomass.

Moreover, there are several studies on regional CGE modeling systems, among which the study carried out at the University of Washington has very complete documentation. It includes a biofuel CGE and an updated model. The model has been applied to several cases and extended by Huang et al. (Huang & Alavalapati, 2009) in their study on policy

implications of second-generation biofuel policy in Florida. The regional CGE model in the framework of the IMpact analysis for PLANning national database (IMPLAN) is used to estimate the impact of bioenergy policy on economic sectors. By giving a policy shock to the regional CGE model, she found out that either an economic or technologic incentive on forest-based bioenergy production has positive impact on Florida's economy and household welfare. However, this static model is not capable of capturing the price path or activity adjustment over time as a result of future target or policy change.

In sum, increased utilization of forest resources for bioenergy poses new challenges for decision making about forest removal and management. The Sub-Regional Timber Supply Model (SRTS) has started to look at the bioenergy production impacts on the sub-regional forest resource, but by design it does not have the bioenergy production sector or agricultural sector. Instead, it takes the agricultural price and future trend of forest product demand/harvest/price due to bioenergy production as given, and then examines changes in various sustainability indicators (Galik, Abt, & Wu, 2009; R. C. Abt, Galik, & Henderson, 2010). Therefore, current models have not addressed the question of sub-regional forest resource sustainability changes in response to specific national biofuel production. Thus, dynamic and spatially detailed modeling efforts that include the biofuel production sector are strongly needed in order to work towards understanding the tradeoff between forest resource sustainability and biofuel production.

2.4 Purpose of Study

The overall purpose of this study is to fill the gap in literature by estimating changes in aspects of forest sustainability related with national biofuel production, while considering uncertainties in policy, market, and technology. The uncertainties are considered because they are very likely to shift the demand/supply for biofuel and thereby change the impacts on forest resources sustainability. In addition, spatial details are accounted for in order to provide insights for regional policy makers.

Forest sustainability can be evaluated against indicators such as forest product market price, inventory, net growth, age class, management type, and so on. So this study's research question for forest sustainability is divided into the following subgroups:

(1) Regional forest market response

Inventory is considered a crucial indicator for timber harvest and resource sustainability. A declining forest inventory signals over harvesting, where removals surpass net growth. Conversely, when net growth is much bigger than removals, the inventory grows too fast and it indicates the need for forest management of density, species mix, wildfire risk and so on (Smith, 2009). Also, the increasing demand for forest biomass encourages more removals and has the potential to push up forest product price. It is expected that the more demand there is for forest biomass, the more removals and higher forest product price there might be. Altogether, they not only influence the economic aspect of forest sustainability, but also change land owners' decision on removals, management, and conversion, which have further impacts on ecological aspect of sustainability, such as biodiversity, wildlife habitat,

and nutrient maintenance. Thus, a quantitative estimation of the indicators is carried out under different scenarios.

(2) Additional harvest and industry displacement

The present study addresses concerns about potential competition for low value forest resources between bioenergy production and the conventional forest industry. The new use of biomass for bioenergy and the traditional use for fiber are competing for forest resources. In particular, with current or future subsidies in the bioenergy industry, traditional industries can be in danger of losing raw materials, which in turn may raise the price of fiber. Thus, this study starts to indentify the quantity of increased forest removal for pulpwood by showing how much is from additional harvest and how much is from displacing traditional industry given price elasticity of bioenergy demand for forest product.

(3) Regional forest residue utilization

Utilizing residues for biofuel production is considered as the lowest cost among all feedstocks, but forest residues contribute to better conditions on harvested sites. They help to preserve soil productivity by containing nutrients and organic matter in the soil, and provide habitat for wildlife. Removing residues without constraints would likely lead to loss in forest ecosystem services and goods. Therefore, sustainable forest management should limit the residue removal rate to the extent that forest can continue to perform these functions in the ecosystem normally. This study starts to look at how much forest residue is needed in order to meet the biofuel demand is examined under uncertainty.

(4) Regional forest land use change

Forest land use can be grouped by management type into natural pine, plantation, mixed pine, upland hardwood, and lowland hardwood. Different management types of forest land have different implications for forest ecosystem services. In the past, natural forests have been increasingly converted into managed forests, which has generated negative impacts on forest sustainability in the form of forest fragmentation and biodiversity loss. On the other hand, an increase in natural pine is beneficial for biodiversity, wildlife habitat, and so on. Forest land use change due to anthropogenic disturbance can be used as an indicator to evaluate sustainability. It also provides key information for strategizing forest management practices to maintain or restore sustainability during bioenergy production. The future forest land use change by management type is projected in this study to help understand forest sustainability.

(5) Regional forest age composition

Forest age class structure is a surrogate for structural condition and can be modified by both anthropogenic and natural disturbance processes, which make it a good indicator for assessing forest sustainability (Didion, Fortin, & Fall, 2007). Anthropogenic disturbances, such as logging activities, are likely to homogenize and simplify forest age structure due to the preference for younger stands (Harvey, Leduc, Gauthier, & Bergeron, 2002). Sustainable forest management tries to maintain age structure within a historic range, which ensures not undermining the ecosystem functions provided by all age classes. Therefore, the

impacts of bioenergy production on forest age class structure are evaluated quantitatively in this study to shed some light on age class's relationship to forest sustainability.

3 METHODS

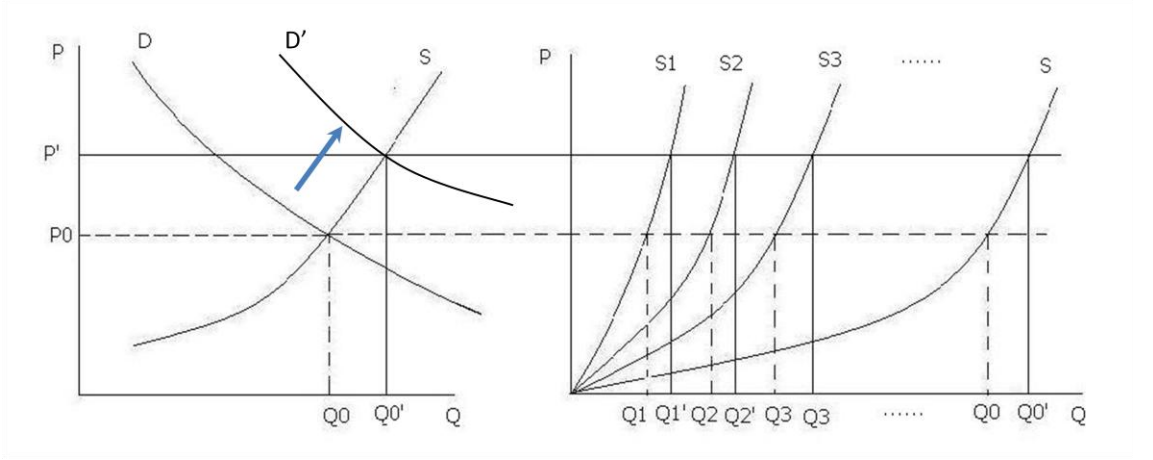
Evaluating changes in sustainability requires measures of local or regional information, which necessitate the use of geographically detailed models. After reviewing current modeling efforts in the literature, I propose to link two existing models, POLYSYS and SRTS, both of which provide spatial detail and yield/cost information, making them good candidates for resource analysis. POLYSYS aggregates county-level biomass yield and cost information for bioenergy production. Its strengths include richness in spatial details and in agricultural and energy crops information. However, it is marked by a lack of dynamic forest response. Meanwhile, SRTS provides dynamic and sub-regional forest resource information in the Southeastern US but agricultural products and bioenergy production are exogenous. The remaining work is to link them together consistently to answer the research question of tradeoffs between forest resource sustainability and biofuel production.

Nevertheless, one might suggest a dynamic model that contains all types of feedstock, their biofuel production, and their resource information. Ideally, such a blend should be the best model since it includes all sectors without having inconsistency issue, but it comes at the cost of very high data requirement and modeling difficulty. Instead, this study takes the approach of enriching two partial equilibrium models and solves the proposed research questions with limited data.

3.1 Framework for Modeling Forest Sustainability Impacts of Biofuel Production

Forest resources are one of many potential feedstocks for biofuel production in the United States. Other feedstock types include agricultural crops and residues, dedicated energy crops, and municipal waste,. Therefore, the demand for forest resources in biofuel production is the outcome of the overall demand for biofuels, and the competition among potential supply feedstocks and technologies. The sustainability implications of the derived demand for forest resources for biofuel must in turn be evaluated in the context of alternative uses for forest resources including pulp and timber.

The theoretical framework for representing demand and supply of biofuels and the competition among potential sources of biofuels and among their respective input factors are depicted in Figure 3.1.



Panel (a) Panel (b)

Figure 3.1 Theoretical Approach Framework

Panel (a) shows the national biofuel supply and demand curves with market equilibrium at quantity Q_0 and price $P_{0.}$. The supply curve S is an aggregation of supply

curves representing the combination of biofuel feedstock and production technologies. These curves denote different types of biofuel production processes, such as wood ethanol, energy crop ethanol, and corn ethanol. These components are depicted as upward sloping supply curves in panel (b), reflecting short-run supply capacities and costs of each ethanol production source. The total supply curve is the horizontal sum of the component curves, which also appears in panel (b). The total supply curve is constructed as the summation of all component production at each given price. For instance, there are three components that constitute "total biofuel," namely "biofuel 1," "biofuel 2," "biofuel 3," and so on. As illustrated in Figure 3.1, to produce same amount of biofuel, biofuel 3 has lower cost than biofuel 1 or biofuel 2. Under a given price such as P_0, the total supply, Q_0 , is distributed among the three supply sources producing Q_1, Q_2, Q_3, respectively. This distribution corresponds to the intersection of each supply curve with the market price level, P_0.

The above depiction of the biofuel market and its equilibrium responds to many factors, such as changes in production technology, subsidy or tax on production, and demand shifts, and so on. Technological change and subsidy/tax may lead to shifts in the total supply, individual supply curves or demand depending on the change's scope and size. For example, technological improvement or tax removal/subsidy imposition for a given biofuel feedstock and technology combination would be expected to increase its share in the market, but may also generate changes in total demand/supply. Similarly, a shift in the biofuel demand curve may give rise to a new price level, depending on whether this is accompanied by supply cost changes or not. For example, if the demand curve D in panel (a) shifts to D', the price and

quantity shift to P' and Q' accordingly, which in turn moves Q_1, Q_2, Q_3 and Q to Q_1', Q_2', Q_3' and Q_0' respectively.

3.2 Model Specification

The modeling system is supposed to account for technology improvement, policy change, and market uncertainty, which should be represented in the linkage between the POLYSYS and SRTS. Thus, a multi-feedstock model (MFM) is built as the link to allow for these changes and uncertainties. The whole methodology involves mainly three models, POLYSYS, MFM, and SRTS. Both POLYSYS and SRTS are already constructed and ready to execute new runs, whereas MFM is developed in the way that is described later in this section.

In order to meet the theoretical needs identified in the previous section, POLYSYS is used to calibrate the production curves of all biofuel types, based on the functions specified in MFM. Subsequently, each type of biofuel production curve is used to derive the demand for its feedstock, also based on the functions in MFM. Then the demand for forest-based feedstock becomes input for the SRTS model to explore the competition with traditional markets and to assess forest resource sustainability. Thus, the MFM is the basis for constructing biofuel supply curves by type and then by input factors. It serves as the link between POLYSYS and SRTS. More importantly, it enables the imposition of policy, demand, and technology simulations to examine the impacts on forest sustainability due to these changes. Specifically, to assess forest resource sustainability due to policy or demand

or technology change, the impacts on total biofuel production have to be allocated among all supply sources of the biofuel, and then passed on from forest-based biofuel to forest resource demand. Therefore, MFM provides a way to distribute total biofuel production to different types of biofuel and then to derive the feedstock demand, so that the forest resource responses can be examined under simulated scenarios.

The inter-relations among the three models are illustrated in Figure 3.2**.** POLYSYS projections of feedstock and ethanol production and prices are used to calibrate the MFM. After all parameters are calibrated, MFM is then used to simulate policy, demand and technology change shocks. The resulting demand for feedstock and agriculture price schedule is then fed into SRTS as an additional demand for pulpwood. As a result, based on the change in demand for forest resources, SRTS generates a new set of results in forest inventory, removal, forest product price, logging residue, age class, and management type by region, species, and year. Furthermore, the logging residues required to produce biofuel as part of the result from MFM is also compared with SRTS results on logging residue production. In the end, pulpwood supply curves embedded in POLYSYS are also compared with SRTS outcomes enriched by POLYSYS and MFM.

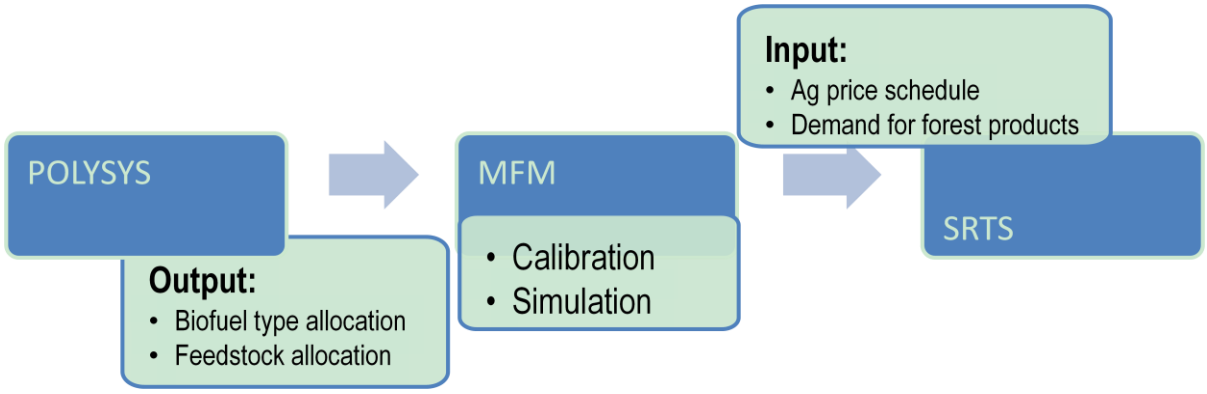


Figure 3.2 Flow chart of the methodology

The rest of this subsection provides overviews of the POLYSYS and SRTS models, while the following main section describes the MFM constructed as part of this study to link the two models in detail.

3.2.1 Overview of the POLYSYS Model

POLYSYS (at Agricultural Policy Analysis Center, University of Tennessee) is an agricultural policy simulation model which is set to the USDA projection (USDA agricultural projections to 2019) as a baseline. Policies are simulated to show the deviation from the baseline case. POLYSYS has several interdependent modules (crop supply and demand, livestock supply and demand, agricultural income) with a recently added forest module. The feedstock considered in POLYSYS includes eight main crops (corn, sorghum, oats, barley, wheat, soybeans, cotton and rice), agricultural residues (corn stover, wheat straw), energy crops (switchgrass, poplar, willow, hay and others) and wood residues. The wood residues in the forest module can be further grouped into logging residues and fuel treatments, urban and mill wood wastes, pulpwood, and other forestland removals. Among all of them, the quantity

of pulpwood for bioenergy production is derived from two sources: (1) pulpwood from additional harvests together with thinning operations, and (2) pulpwood displaced from existing forest industry.

3.2.2 Overview of the SRTS Model

The Sub-Regional Timber Supply Model (SRTS), developed by Abt, R. et al., has already been applied to reflect potential impacts from added bioenergy demand (Abt, Cubbage, & Abt, 2007; Galik, Abt, & Wu, 2009). This modeling system applies a standard empirical framework to subregional inventory data in the South. Timber market and inventory modules interact to reach dynamic equilibrium. In the timber market module, price change is first solved through subregional market equilibrium and then the price and supply shifts are used to calculate harvest change in each subregion. Forest product demand is modeled as a function of stumpage price and demand shifts, while product supply is a function of stumpage price and inventory. The product price and harvest levels by species, type, sub-region and ownership by year are determined simultaneously at market equilibrium (Abt, Galik, & Henderson, 2010). In the inventory module, a program goal of forest harvest across owner, management type, and age class is solved for each region owner and then allocates this harvest across management types and age classes. Once the removal by region, owner, and management type is determined, the inventory for the next year is actually equal to the inventory for this year plus growth minus removal in this year. For the following year,

the forest ages one year and the process starts over. Thus, the two modules are linked through inventory and timber removal each year. (Abt, Cubbage et al. 2000)

This dynamic model utilizes economic supply and demand data from across the U.S. south, and predicts future timber inventory, removals and prices by species, ownership, age class, and management type for sub-regions in the 13 southern states over time. The Forest Inventory and Analysis Program (FIA) data provides the benchmark for constructing the model's base year. The driver of the projection can be demand for forest resources, forest product price, and forest harvest.

As a partial equilibrium model, SRTS models only forest sectors while regarding the agriculture sector as exogenous. Nevertheless, bioenergy policies have direct impacts on the agriculture sector, transportation sector, and so on. A close look at the interactions between sectors is indispensible. Additionally, it is notable that the SRTS model only applies to 58 regions of 13 states in the southeast, but POLYSYS results used for calibration are at the national scale. Thus, the county-level results in POLYSYS are aggregated over sub-regions, state, and southeastern states levels by forest biomass road-side price and year.

3.3 Multi-feedstock Model (MFM)

3.3.1 Theoretical Model

Competition among different sources of biofuels represented in the MFM can be divided into two steps:

(1) Derivation of demand for a specific biofuel supply source from the production function for total biofuel supply, and

(2) Specification of production functions for each supply source of biofuels.

Theoretically, applying duality theory (Diewert, 1973), a production maximization problem can be solved as a cost minimizing problem. Thus, the production functions in both steps can be represented by cost functions. I assume that the biofuel industry as a whole, as well as specific biofuel industries, display twice differentiable cost functions. A well-defined cost function should have the following properties:

(1) Non-decreasing in variable factor prices: requires a positive first derivative of cost function.

(2) Concavity in variable factor prices: implies a negative semi-definite Hessian matrix.

(3) Homogeneity in variable factor prices: Changing all prices proportionally will not change relative price bundles.

Additionally, the cost functions are assumed to have constant returns to scale.

Thus, the cost function on the first level is specified as:

$$C=f(P_1, P_2, \ldots, X) \quad (1)$$

where C=aggregate cost of all national ethanol supply,

Pi=price of biofuel from source i, and

X=Total ethanol output.

Similarly, the cost of biofuel of type i can be written as

$$C_i=g(P_{i1}, P_{i2}, \ldots P_{ij}.., X_i) \quad (2)$$

Where C_i = aggregate cost of biofuel type i,

P_{ij}=price of input factor j to produce biofuel component i, and

X_i=output of biofuel component i

This cost function should also follow the three properties of non-decreasing, concavity and homogeneity in factor prices.

Applying Shephard's lemma, the partial derivative of a cost function with respect to the input prices gives the demand for each input. Thus, the demand for ethanol of type i, X_i, is derived from applying Shepard's Lemma to the total ethanol cost function, and the demand for inputs into the production of each type of biofuel x_{ij} from the corresponding cost function as given respectively in Equations (1) and (2):

$$x_{ij} = \frac{\partial C}{\partial Pij} = \frac{\partial C}{\partial Pi} * \frac{\partial Ci}{\partial Pij} \quad (3)$$

Empirical Specification of the MFM

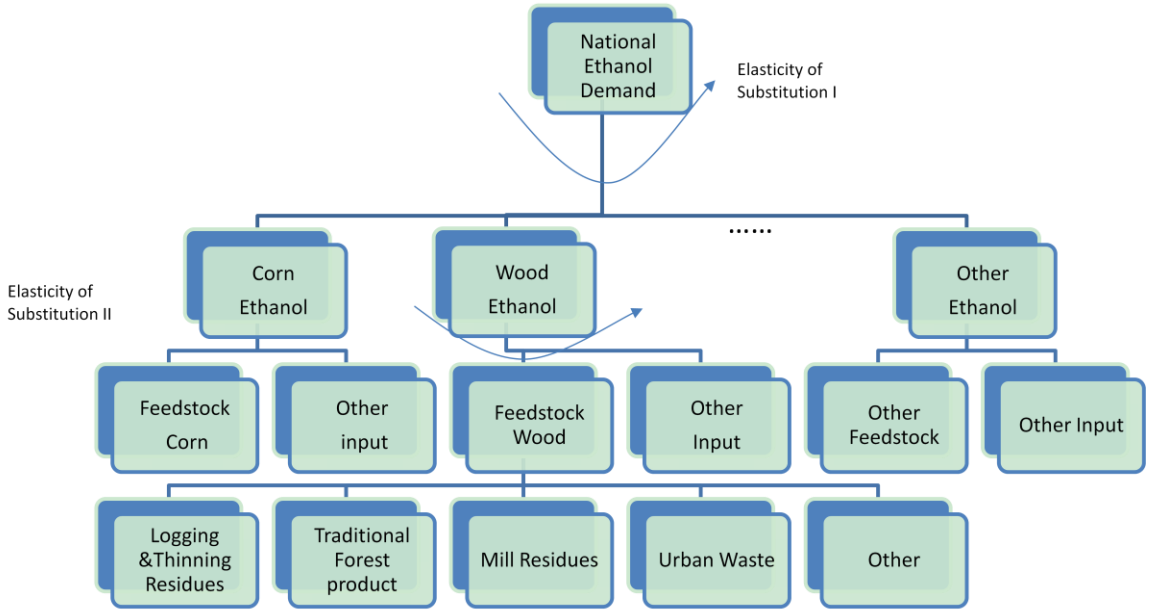


Figure 3.3 MFM Structure

Figure 3.2 illustrates the three-level nested functional form representing the supply of ethanol and the competition among different feedstock sources. At the top level, ethanol cost/price is specified as a function of the cost of producing different biofuel types.

C = h (cost of producing corn biofuel, switchgrass biofuel, corn stover biofuel, forest residue biofuel, short-rotation woody crop biofuel, and other, total biofuel production x)

Given the assumption of constant returns to scale, the cost function can be written as:

$C = x * UC$, with the unit cost function UC thus written as

$$UC = \frac{C}{x} = \bar{f}(c_1, c_2 \dots c_i, \dots) \qquad (4)$$

where i represents biofuel type, such as corn biofuel, corn stover biofuel, forest biofuel, etc., and c_i is the unit cost of producing biofuel i. The Constant Elasticity of Substitution (CES) function is assumed for the unit cost, as it is widely adopted in multi-level calibration models.

With elasticity of substitution $\sigma = \frac{1}{1-\rho}$, A CES cost function is defined as:

$$C = \phi(\sum_i \alpha_i C_i^{\rho})^{1/\rho} \quad (5)$$

where $\phi > 0, \alpha_i > 0, \ and \ \sum_i \alpha_i = 1.$

The demand function for ethanol of type i, Xi, from the CES function based on Shepard's Lemma is given as: $x_i = \frac{\partial C}{\partial C_i}$, and x_is are the components which produce x

On the second level the cost of producing biofuel i is a function of all input factors and total production of biofuel i, such as capital, labor, feedstock, energy, service, and other.

$$C_i = \bar{C}(P_{i1}, P_{i2}, \dots P_{ij} \dots, x_i) \quad (6)$$

where j denotes various input factors such as capital, labor, feedstock, energy, and service, and P_{ij} is the price of input factor j in producing a unit of ethanol i. Based on a constant return to scale assumption, the unit cost of producing biofuel i can also be expressed as

$$c_i = \frac{C_i}{x_i} = \bar{C}(P_{i1}, P_{i2}, \dots P_{ij} \dots) \quad (7)$$

Then the Leontief function is applied for the unit cost of biofuel, in order to be consistent with the approach to biofuel cost in POLYSYS. The Leontief function is a special

case of constant elasticity of substitution functions with the elasticity of substitution equalling zero. Intuitively, it represents the type of technology that would cause input factors not to be substitutable under a given study's time frame. Nonetheless, the Leontief function here is calibrated to POLYSYS results year by year. Thus, the technology is not necessarily assumed to be fixed for all the years in question. Rather, it shows the technology improvement assumed in POLYSYS.

Thus, the unit cost of biofuel i follows the function below.

$$c_i = \bar{C}\left(P_{i1}, P_{i2}, \dots P_{ij}, \dots\right) = (b_{i1}P_{i1} + b_{i2}P_{i2} + \cdots b_{ij}P_{ij} \dots) * b_{0i}, \quad (8)$$

where b_{0i} is a technology factor.

The demand for inputs into the production of each type of biofuel, xij, for the Leontief function is simple and represented by: xij = x*bij.

According to Shepherd's lemma, the derived demand for input j is the derivative of total cost to the input price. So the derived biofuel demand for input j is

$$x_{ij} = \frac{\partial C}{\partial P_{ij}} = x * \frac{\partial UC}{\partial P_{ij}} = x * \frac{\partial UC}{\partial c_i} . \frac{\partial c_i}{\partial P_{ij}} \quad (9)$$

All biofuel demand is assumed to be met by national supply. So we have the following equilibrium:

$$x = Q_D \quad (10)$$

The bottom level in the figure of MFM structure shows the woody biomass sources, including forest-based biomass, mill residues, urban waste, and others. Forest-based biomass here refers to thinning and logging residues and existing forest products.

In Perlack's Billion Ton Study-Update results (B. Perlack et al., 2011) for $60/ton at roadside scenario, the proportions of woody biomass are as follows: 42% from urban municipal solid waste (MSW) and mills, 43% logging residues and 2% from pulpwood. However, MSW is very dispersed and hard to collect, and mill residues are almost used up on site, which leaves pulpwood as the strongest candidate after logging residues run out. Pulpwood is relatively inexpensive within an established market, compared to sawtimber. Pulpwood has a commercial value that is lower than other forest products. Under a competitive market condition where the pulpwood price is high enough, it is likely to be harvested before it grows to a bigger size tree for higher-value products. Pulpwood-sized roundwood can be acquired through harvesting more pulpwood-sized trees and taking pulpwood product away from current conventional markets.

According to most researchers (Carter, 1992; Liao & Zhang, 2008; Newman, 1987; Newman & Wear, 1993; Polyakov, Teeter, & Jackson, 2005; Prestemon & Wear, 2000), the short-run pulpwood supply market is very price inelastic. A small demand change can lead to a bigger change in pulpwood price. The increase in demand shifts the demand curve to the right and pulpwood supply shifts with the price change, too. This relationship is illustrated in Figure 3.4.

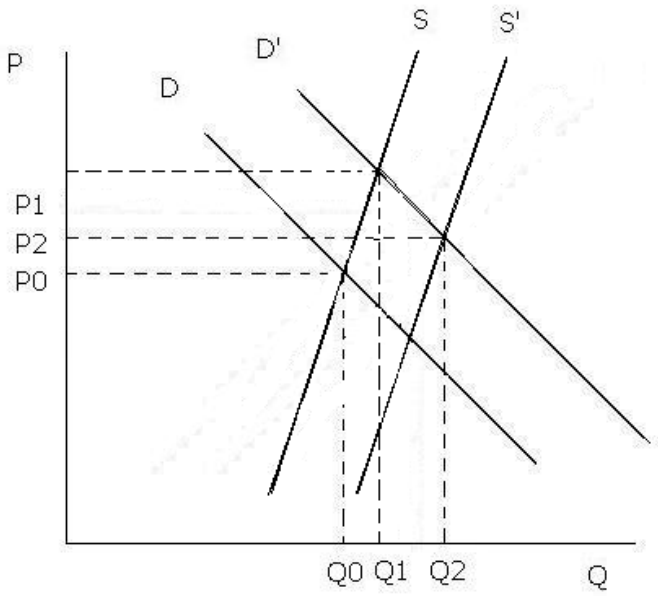


Figure 3.4 Pulpwood theoretical supply and demand

In the short run, extra demand for pulpwood shifts the demand curve to the right to D', which intersects with supply curve at price P1, higher than P0. The supply of pulpwood can adjust to this price change by shifting outward to S'. However, since the pine pulpwood supply outward shift lags demand outward shift, the ending price would be lower than P1 but still higher than P0. The pulpwood demand for bioenergy production can come from additional harvest and also replacement from existing pulpwood industry.

Some researchers (Abt et al., 2010) have shown that the demand for energy would tap into the existing wood product sector by doubling the harvest of pulpwood. This would also result in a significant upward pressure on wood product prices, and would slow down the payback period of timber investment. In this scenario, direct competition with existing wood products industry will take place. Therefore, the pulpwood demand for bioenergy production

is added to existing industrial demand for forest products in SRTS demand driven runs, when biomass demand exceeds logging residue availability.

3.3.2 Data, Parameter Estimation, and Calibration of MFM

3.3.2.1 Data

The report "USDA agricultural projections to 2019" (USDA, 2010) projects agricultural markets over commodities, trade and aggregate indicators of the U.S. agricultural sector through 2019. It also takes into consideration the continued demand for biofuel in the U.S. Biofuel production is projected based on historical biofuel production data, USDA interpretation of government plans, and potential investment. Also, ethanol blended into E10 and E85 market is considered to be limited. The tax credit to blenders and 54 cent tariff on imported ethanol are assumed to be in effect in the projection period.

In the POLYSYS baseline, the agricultural projection is extended to year 2030 by extrapolation. The POLYSYS result is calibrated under the US Energy Independence and Security Act (EISA) scenario, in which the corn biofuel and advanced ethanol reach 15 billion gallon per year and 20 billion gallon per year by 2022 respectively, and both stay the same throughout the year 2030. Compared to the USDA projection baseline, an additional amount of 0.29 BGY Biodiesel is produced by 2022 and then throughout 2030. Meanwhile, the bio-electricity generation hits the demand of 230 billion KWh in 2022 and continues to grow after that. All the equations are calibrated to the simulation output designed to meet EISA-RFS mandates and also some level of bio-electricity and biodiesel targets, as specified in POLYSYS.

The demand projection on biofuel production used in Scenario D4 is from the Annual Energy Outlook 2010 (AEO) of the Energy Information Administration (EIA). EIA projects energy production, consumption, technology, market trends and their direction by year till 2035, assuming current laws and regulations are not changed in the projection period. The projections are generated from the NEMS model, which includes interactive modules to represent the supply, demand, and conversion sectors of domestic energy markets, as well as international and macroeconomic modules. The laws and regulations considered in the report include an EPA waiver for E15 built in 2007 or later, the Food, Conservation, and Energy Act of 2008, the EISA2007, and so on.

As noted that POLYSYS simulates national markets, while SRTS was made for the 13 states in the Southeast. To solve the scale divergence, the present study aggregates the logging residues, pulpwood, for bioenergy in POLYSYS results over all counties in the 13 southern states. Then a lookup table of pulpwood and logging residues for bioenergy from POLYSYS results by state, road-side price, and year is generated for the Southeastern states. The table can also be used to generate logging residue and pulpwood supply curves, which compare available feedstock quantities versus road-side prices. This lookup table is actually a summary of POLYSYS and is then directly used for SRTS demand runs. However, it should be noted that the pulpwood price derived in POLYSYS is a summation of both stumpage price and harvest cost. Summaries of POLYSYS results for pulpwood and logging residue supply for bioenergy production from the Southeastern states are shown in Appendix A.

The pulpwood and logging residue demand in the Southeast for bioenergy can be found through the lookup tables based on the year and road-side price result. Then the extra pulpwood demand and agricultural price schedule are used to drive SRTS demand runs.

3.3.2.2 Parameter Estimation

To simplify calibration, I make the assumption that there is only one representative technology per feedstock to represent the POLYSYS results. Thus, this representative technology acts as the average technology for each type of biofuel production and it is calibrated to the technology progress embedded in POLYSYS each year. In order to allow for flexibility in this assumption, a greater technology improvement is assumed in one scenario that is discussed later.

The variables that require calibration include ethanol supply (total and by type) and corresponding prices, as well as input levels and their prices for each type of ethanol. Given this, the main parameters to fully specify the two CES cost functions are the share parameters (a_i and b_{ij}) and the elasticities of substitution, σ , as illustrated in the table below.

Table 3 Parameters and their derivations

Parameters	**Source**
Elasticity of substitution σ	Estimated from POLYSYS under multiple demand driven runs
Elasticity of substitution for level 2	Fixed I-O Coefficient (Leontieff)
CES share parameters (a_i and b_{ij})	Calibrated to POLYSYS under RFS

The share parameters are calculated directly from the POLYSYS results at the benchmark. Indices i and j denote the ethanol types and input factors. However, there is no

commonly adopted number for this elasticity. The bigger it is, the easier the components are to substitute each other. However, in order to make the MFM consistent with the POLYSYS, the parameter theta is estimated through multiple ethanol demand driven runs in POLYSYS. With more than one demand driven run, the shape of the curves in panels (a) and (b) of Fig X can be estimated for the CES function econometrically.

After some rearrangement and algorithmic operations of the CES function (Berndt, 1976), the market productivity relation can be expressed as

$$\ln\left(\frac{x_{it}}{x_t}\right) = \ln\alpha_i + \sigma \ln\left(\frac{p_t}{p_{it}}\right), \quad (11)$$

where i and t denote types of biofuel and year, as defined previously. It can then be used to estimate or test the substitution of elasticity for CES function econometrically. The demand runs used for this estimation include (1) RFS plus biopower demand, (2) 14 billion gallons by 2012, (3) 23 billion gallons by 2017, and (4) 35 billion gallons by 2022. The result shows that theta averages about 0.7. Then 0.7 is used throughout this study for all scenarios. Therefore, the default assumption is that substitution relationship among types of biofuels does not vary with policy, technology, or biofuel demand.

As discussed previously, the functional form for the biofuel production in the second level is assumed to be linear, which represents a perfect substitution function, and the elasticity of substitution approaches positive infinity. In addition, other parameters in the MFM, such as a and b, are estimated through the calibration against POLYSYS demand driven run to satisfy RFS and some power generation demand.

3.3.2.3 Calibration of MFM

With all the data, a step-by-step calibration process is described below. All notations with a bar on top imply base year levels of the variables. Under a perfect market with zero profit, the total cost of ethanol C is equal to the revenue, ethanol price P multiplied by ethanol production x.

After calibration to the benchmark with unity at the reference point, the unit cost function can be expressed as

$$C = \bar{C}\left[\sum_i a_i\left(\frac{p_i}{\bar{p}_i}\right)^{1-\sigma}\right]^{\frac{1}{(1-\sigma)}}, \quad (12)$$

where $\sigma = \frac{1}{1-\rho}$, $\bar{C}$ is the benchmark unit cost, and a_i is the benchmark value share of i which can be written as $a_i = \frac{\bar{p}_i\bar{x}_i}{\sum_i \bar{p}_i\bar{x}_i}$.

By substitutingc_i, $\bar{c}_i$ for p_i, $\bar{p}_i$ and $\bar{p}$ for$\bar{C}$, the unit cost function becomes:

$$p = \bar{p}\left[\sum_i a_i\left(\frac{p_i}{\bar{p}_i}\right)^{1-\sigma}\right]^{\frac{1}{(1-\sigma)}}, \text{ where } a_i = \frac{\bar{p}_i\bar{x}_i}{\sum_i \bar{p}_i\bar{x}_i} \quad (13)$$

For the unit cost function of ethanol i, a linear price form is assumed. So it can be written as

$$p_i = \bar{p}_i\left(\sum_j b_{ij}\left(p_{ij}/\bar{p}_{ij}\right)\right), \text{ where bij} = \frac{\bar{p}_{ij}\bar{x}_{ij}}{\sum_j \bar{p}_{ij}\bar{x}_{ij}} \quad (14)$$

Similarly, the calibrated demand for component biofuel i can be expressed as:

$$x_i = \frac{\partial C}{\partial Pij} = \bar{x}_i\left(\frac{c(p)\bar{p}_i}{\bar{c}p_i}\right)^{\sigma}\frac{x}{\bar{x}} \quad (15)$$

where $\bar{x}_i$, $\bar{p}_i$, $\bar{c}$ and $\bar{x}$ are the benchmark quantity and price of biofuel i, unit cost of total biofuel and its production respectively. After substituting c for p, the derived demand for ethanol i becomes:

$$x_i = \bar{x}_i \left(\frac{p\bar{p}_i}{\bar{p}p_i}\right)^{\sigma} \left(\frac{x}{\bar{x}}\right) \quad (16)$$

where x_i is the ethanol i production and $\bar{x}_i$ is its benchmark.

Also the derived demand for input factor j when producing ethanol i is

$$x_{ij}\bar{p}_{ij} = b_{ij}x_i\bar{p}_i \quad (17)$$

In addition, ethanol price is used as proxy for ethanol production cost:

$$c = P,\ c_i = p_i \quad (18)$$

The demand for biofuel Q_D is considered equal to biofuel production nationally.

$$x = Q_D \quad (19)$$

Then, all the equations (Equation 13-Equation 19) are solved simultaneously in the mathematical programming software General Algebraic Modeling System (GAMS) and the Non-linear Programming (NLP) solver are used for the study.

The fully calibrated MFM has 27 equations and variables in the MFM model, as shown in Table 4. Then the model system is ready for simulations.

Table 4 Balance table of EQUATIONs (# 27) and Variables (# 27):

	Quantity	Price
Total ethanol	EQTETH1 (fixed)	EQCOST
Type of ethanol (i) i=Corn, Stover, swgrass, poplar, wood, other	EQSMD1(i)	EQPSMD(i)
Inputs (j) into each type of ethanol i j=feedstock, other	EQSMD2(i,j)	Fixed

4 SCENARIOS AND SIMULATIONS

In order to explore the impacts of future uncertainties on forest sustainability, several scenarios are designed to guide models in the present study. As described in methodology framework, policy, demand, and technology are likely to shift the supply curves of different types of biofuels and thus the demand for forest biomass. Therefore, the RFS plus electricity generation is set as baseline scenario for comparison with simulation scenarios, which are tax credit removal, AEO demand pattern, and technology improvement scenarios. In addition, a sensitivity analysis on logging residue utilization rate is also carried out. Table 5 shows the construction of all scenarios based on different demand (D) for pulpwood, and their respective outcomes of total pulpwood supply. These demand scenarios start with the base demand, and then have various levels of increased demand.

Table 5 Scenario construction, and pulpwood demand and supply

Demand Scenario		Bio-demand for pulpwood	Total demand for pulpwood	Total pulpwood supply
D0	0	0	base	s0
D1	RFS + Elec	d1	base+d1	s1
D2	Tax Credit	d2	base+d2	s2
D3	Technology	d3	base+d3	s3
D4	New Demand	d4	base+d4	s4
D5	Utilization rate	d5	base+d5	s5

The MFM model must be balanced in the number of equations and variables in order to produce reasonable simulation outcomes. Relaxing some variables while fixing others can lead to balanced results. The simulations are organized in five groups consistent with the previously discussed scenarios. Scenario D1 is the benchmark for simulations in D2, D3 and D4, and D1 itself is compared with D0 to show the effects of adding bioenergy demand for pulpwood. All shocks are imposed on year 2022 and the bio-demand for pulpwood keeps the same as that in 2030 for the rest of the time period.

4.1 Baseline scenarios

- **No bio-demand for pulpwood (D0)**

Demand for forest resources in the South is very complex due to the region's multiple products. Total timber production doubled between the 1960s and the 1990s, though an "adjustment" period has halted this rapid growth since the late 1990s (Wear et al., 2010). Currently, we observe a short-run decline in the forest product market as a result of the economic recession. However, a decline in pulpwood would contribute to a further drop in

sawtimber product supply, which likely leads to a higher demand for sawtimber in the longer run. Therefore, this study assumes the demand for pulpwood products drops by 10% from 2007 to 2017 and then stays at the same level until 2037, whereas the demand for sawtimber products falls by 30% and bounces back by 2016 and then keeps on increasing for the rest of the period, reaching 26% by 2037.

Changes in this assumption about pulpwood demand do not have significant impacts on scenario simulations since they are compared with RFS scenarios instead. Meanwhile, agricultural price schedule is set to be the agricultural rent projection of eight main crops in the USDA projection and POLYSYS result. This base scenario serves as a control for not considering bioenergy demand for pulpwood. It sets the baseline to compare the forest sector with and without the demand to utilize industrial forest product for bioenergy.

- **RFS Scenario (D1)**

The calibrated parameters represent the feedstocks/biofuels allocation each year that satisfies the requirements of EISA-RFS (EPA, 2007) as well as the annual electricity generation of 230 billion kWh and annual bio-diesel production of 0.3 billion gallons. Thus, the feedstock result from this base scenario D1 represents the resources required to produce enough biofuel to reach the RFS target, including corn, corn stover, switchgrass, poplar, forest biomass, and others.

The POLYSYS demand run under RFS provides information on agriculture price schedule and woody biomass demand each year. The pulpwood demand in the Southeast for bioenergy by year is obtained from POLYSYS results, using the lookup table mentioned

earlier. This pulpwood demand for bioenergy schedule is then added to current demand for industrial pulpwood in SRTS to drive new runs. This increased rate of pulpwood demand is assumed to be the same for both softwood pulpwood and hardwood pulpwood. This scenario is regarded as the baseline for policy change, demand shift, and technology improvement scenarios.

4.2 Tax Credit Removal Scenario (D2)

By changing the tax credit/subsidy examined in the model for a certain year, the feedstock demand and supply for corresponding biofuel is adjusted. Then the new demand for feedstock, which represents the new market condition for each feedstock, is fed into the dynamic model for more detailed information. In this way, the policy change impact on forest resource markets can be studied.

To examine the impact of tax credit removal, a new parameter is added to the model, tax rate t. At baseline, t equals zero, but it can be set as a negative number to represent a tax removal or subsidy. Different tax rates can be imposed on any type of biofuels with index i. Therefore, the type i ethanol price equation becomes

$$p_i = \bar{p}_i(1 + t_i)(\sum_j b_{ij}(p_{ij}/\bar{p}_{ij})) \quad (20)$$

Where i and j denote biofuel type and input factor, as defined before.

In this scenario, the removal of corn ethanol tax credit $0.45 per gallon is considered, which is divided by projected corn price in 2022 to get the parameter t (corn) = 23.8% for that year.

4.3 Technology Change Scenario (D3)

There are three ways to control for the technology progress. The first one is to expand the feedstock i to include more feedstock sources than studied here. Secondly, the elasticity of substitution can be changed to reflect future development in technologies. The last one is to change the unit cost of the type of biofuel where technology improvement takes place, and it is also the approach taken in the technology change scenario of this study. Thus, the model is flexible enough to accommodate exogenous changes in feedstock or technology.

In the calibration, the technological developments required f producing each type of ethanol is already set up in the POLYSYS results. In order to test its sensitivity, this scenario is designed to accommodate a bigger improvement in conversion technology.

It is assumed that due to a technology breakthrough in the future, the wood-based biofuel price drops by 25% by the end of year 2022. The price drop can be added as a negative tax rate, in the same way as a subsidy. The rationale behind this is that technological improvement represents a cost saving that can be also achieved by subsidy or tax reduction. They have the same effect in cost saving, but differ in the source, which is not differentiated in the calibration model. Therefore, the simulation can be written as adding 25% tax credit for wood-based biofuel, which is t(wood)=-25%.

4.4 Demand Pattern Change Scenario (D4)

The POLYSYS assumption MFM is calibrated to assure the fulfillment of RFS2 by 2022, representing a production of 36 billion gallons of biofuel with 21 billion gallons of cellulosic and more advanced biofuel. Nevertheless, the projection differs from the AEO

(2010). It concludes that the RFS2 can be exceeded by year 2035 but cannot be achieved by the year 2022. To examine the effects of the biofuel demand pattern on the model, the MFM biofuel demand is re-calibrated to AEO projection and then the rate of change in demand for pulpwood is added to SRTS.

In the AEO 2010 projection, EISA2007 RFS targets are not met in 2022 but are surpassed later. Only 25.7 billion gallons are achieved in 2022 due to technological and economic difficulties. Figure 84 of the AEO 2010 Projection reports RFS credits earned in selected years from 2008 to 2035. One credit denotes the ethanol equivalent by gallon in that year. If the RFS mandate remains at 36 billion gallons after 2022, it intersects the AEO projection in approximately year 2030 at 36 billion gallons. As we can see in Figure 4.1, the two lines cross around year 2014 for the first time. After year 2022, RFS2 mandates remain at the same level, whereas the AEO projection catches up and surpass 36 billion gallons in year 2030 and continues to grow.

Nevertheless, the simulation of this new demand pattern is only carried out throughout 2030, in that the POLYSYS benchmark (D1) is projected to 2030 without extending to 2035. The bioenergy demand for pulpwood outside of projection time period is maintained at the same level as the last year of the projection period, which is 2030 in this case. However, the AEO projection goes further beyond this level and reaches 42.86 billion in 2035, as shown in Table 6.

Table 6 EISA2007 RFS credits earned in selected years, 2008-2035 (billion credits)

	Corn-based	Cellulose Based	Imports	Biodiesel	BTL	Other Feedstock	total
2008	9.29	0	0.7	1.04	0	0.27	11.34
2012	13.4	0	0.3	1.48	0.09	0.95	16.29
2022	14.23	2.1	1.77	2.59	2.74	2.26	25.69
2035	15	5.11	5.1	2.94	12.5	2.21	42.86

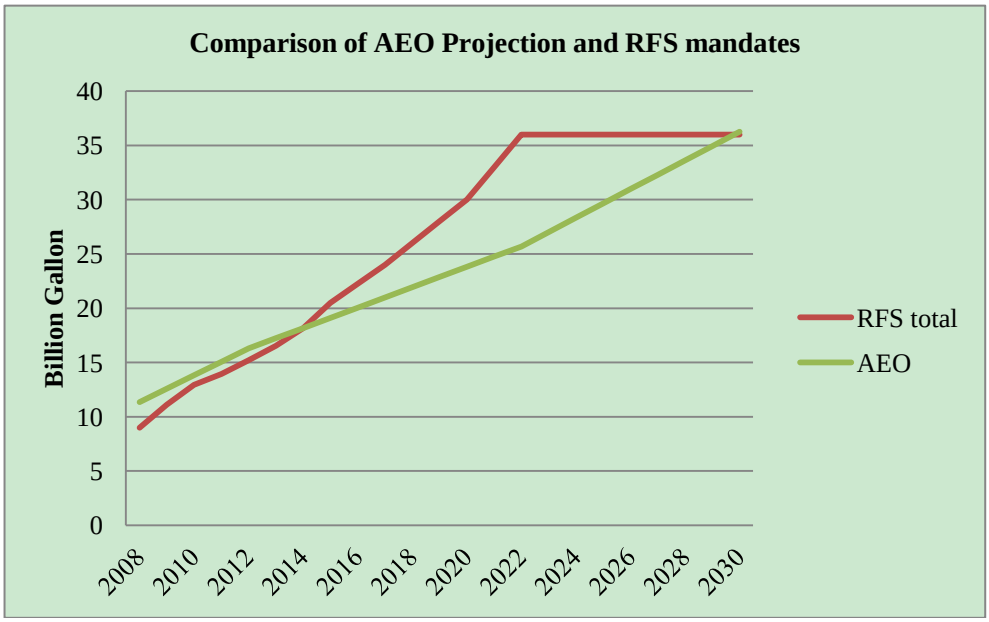


Figure 4.1 Comparison of AEO and RFS (Unit: Billion Credits)

4.5 Sensitivity Analysis (D5)

Logging residues cannot be removed without constraints. This is due to several considerations, including environmental and ecological reasons, area accessibility, collection technology, and cost-effectiveness. Residues left on the site can provide wildlife habitat,

reserve nutrients and organic matter, and reduce soil erosion, but it is unclear how much can be removed before impairing these functions. The rate of logging residue removal over the total logging residue in the field is referred to as the utilization rate. Utilization rate varies from location to location. For sustainability considerations, it depends on the slope, soil and nutrient condition, wildlife habitat, etc of the location. Abt et al. (2010) take a gradual increase approach for residual utilization rate, which allows the rate to peak at 50% in 2020. Perlack (2005) indicated that removing 70% of logging residues on slopes less than 30% and 50% on steeper slopes are reasonable estimates for sustainability purposes.

The scenario D5 is designed to evaluate the sensitivity of logging removal rate on final results. 25% is applied as the maximal utilization rate for all regions in the Southeast. The deficit in logging residues is assumed to be met by additional pulpwood supply.

5 RESULTS

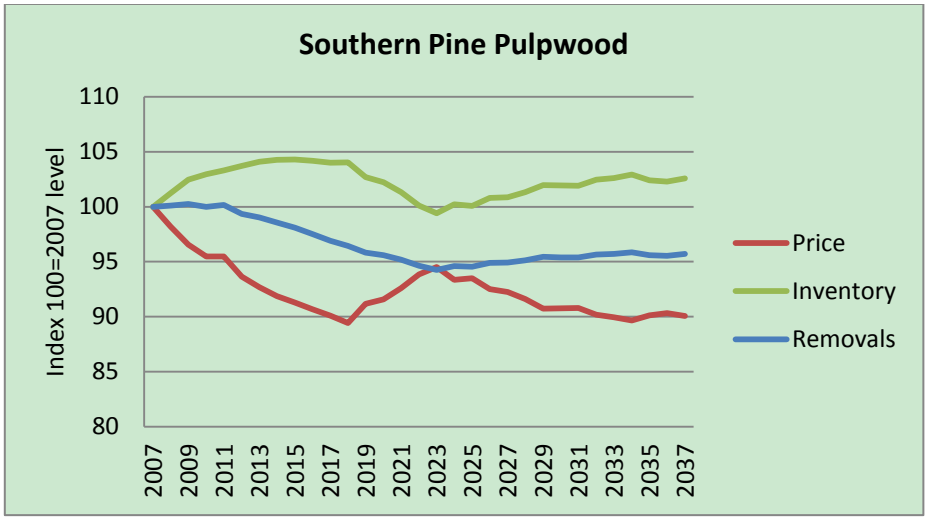
For each scenario, a set of results is generated to examine the biofuel impacts on aspects of forest sustainability, which include forest market response, industry displacement, logging residues, forest land use and management type change, and age class structure.

5.1 Scenario D0

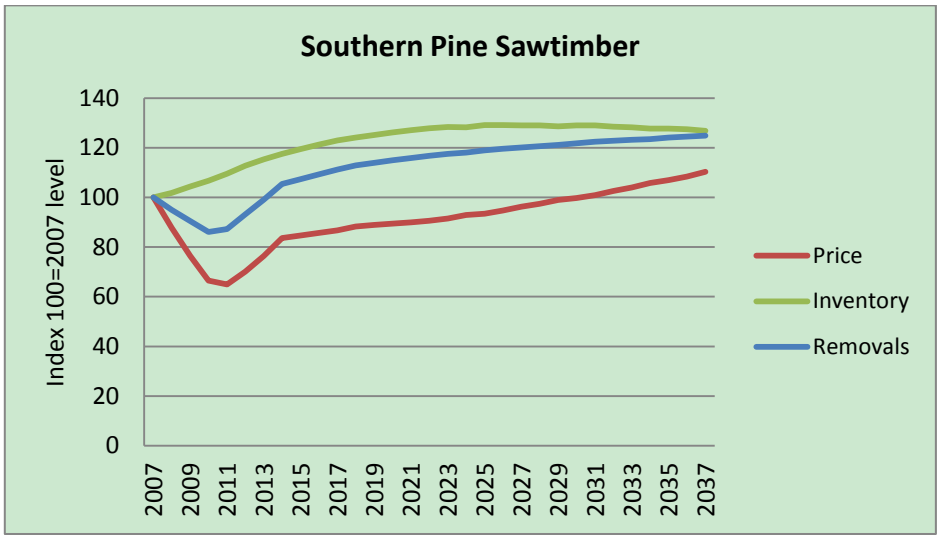
- Existing forest product market response

The trend of baseline inventory, removal, and price is projected in Figure 5.1. The red, green and blue represent price, inventory and removal, respectively. The numbers on the vertical axis are index based on year 2007 and equal 100.

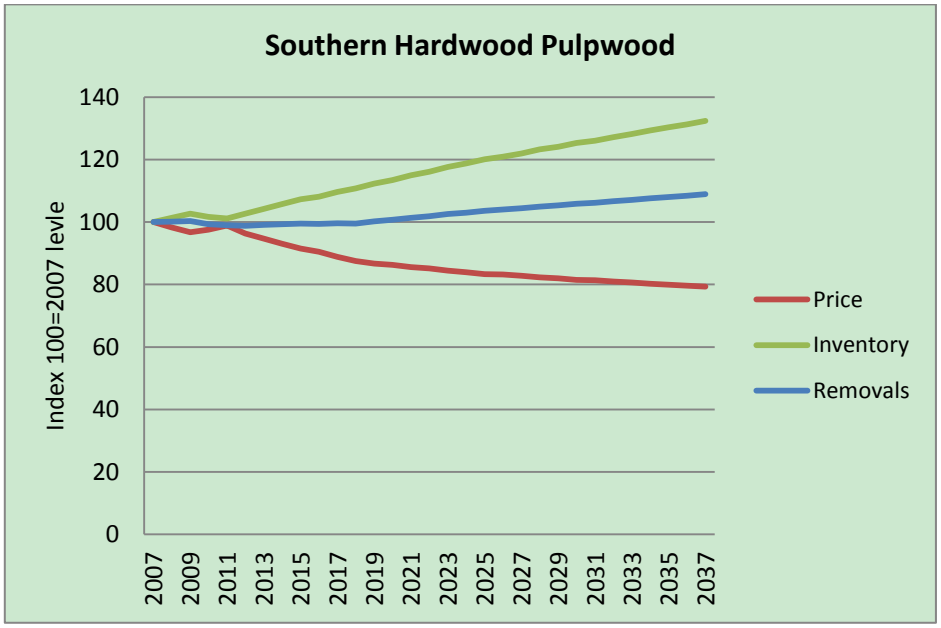
Figure 5.1 market projection of four forest products under baseline D0



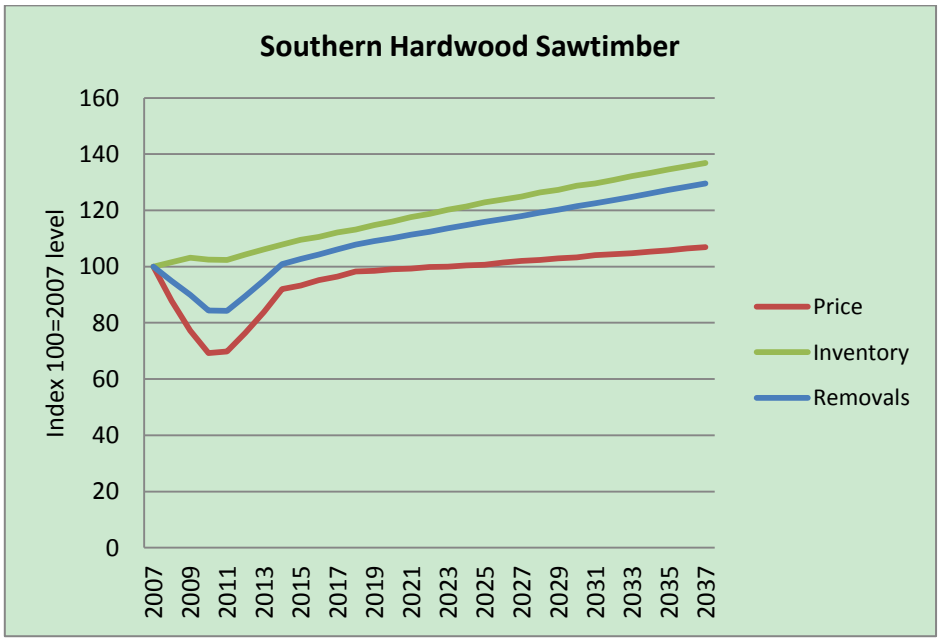
(a) Southern pine pulpwood market response



(b) Southern pine sawtimber market response



(c) Southern hardwood pulpwood market response



(d) Southern hardwood sawtimber market response

It can be observed that pine pulpwood is the least volatile in price, inventory or removal, while pine sawtimber and hardwood sawtimber markets have a very similar response to each other. The hardwood pulpwood price declines further than softwood pulpwood by approximately 20%, compared to 10% in 2037. The price of sawtimber products falls until around year 2011 and then comes back and surpasses 2006 levels by 2037, by 10% in softwood sawtimber price and 7% in that of hardwood sawtimber.

The removals of all forest products, except pine pulpwood, decline in the first few years, bounce back, and then go beyond 2007 levels in the end. Pine pulpwood removal declines without coming back to the 2007 level, and it falls by 5% of 2007 level in 2037.

The inventory levels of all products are above their 2007 levels in 2037, while the biggest increase lies in hardwood sawtimber inventory, approaching a 40% increase in the end of the time period. The inventory of pine pulpwood falls below the 2007 level in year 2023, which contributes to the drop in the slope of pine sawtimber inventory starting in 2023. The pine sawtimber supply starts to deplete its net growth when there is less pine pulpwood growing to the bigger size product, sawtimber; to the 10% increase in pine sawtimber price is attributable to the same depletion. The increase rate of pine sawtimber inventory is getting close to that of its removal rate at the end of the model's time coverage, which signals a possible inventory decline in the future.

The regional changes in inventory of pulpwood by species are shown in the maps below. The red and green colors denote negative and positive changes in inventory from 2007 to 2037, and the darkness represents the size of the changes. As can be seen from the

maps, all states but Kentucky will experience a decline in softwood pulpwood inventory, while hardwood pulpwood inventory increases in each of the southern states.

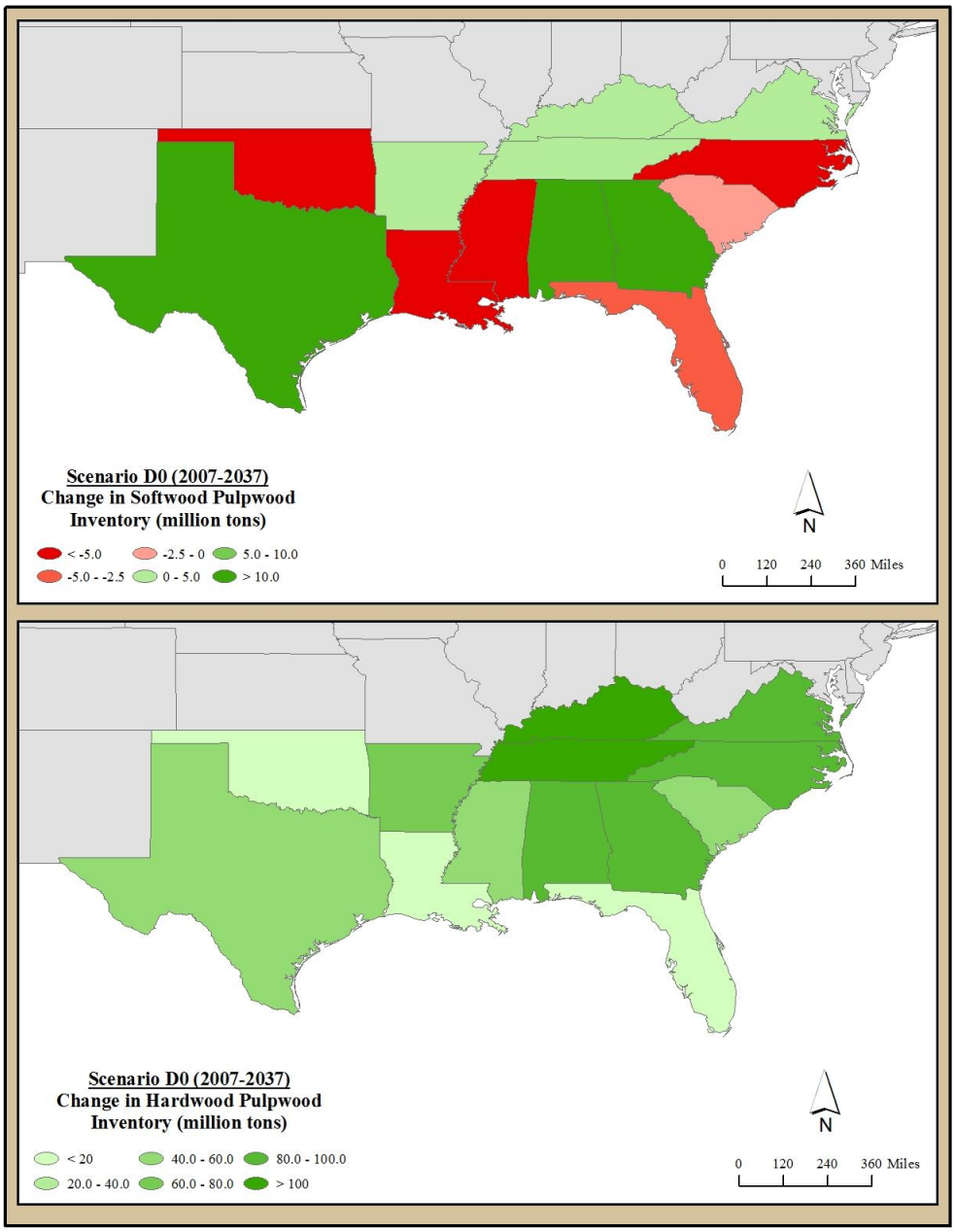


Figure 5.2 Maps of pulpwood inventory change by species and state under Scenario D0

- Logging residues

Logging residue removal has been a heated topic in sustainability literature. How much can be removed still remains a question. Logging residues are left on the ground because they are not worth removing. They also maintain soil nutrients, organic matter, and thus soil productivity. Unlimited removal could lead to soil erosion and productivity loss. A sustainable extraction of forest residues should be conducted for sustainability concerns. Such extraction can be achieved through implementing best management practices (BMPs), Biomass Harvesting Guidelines (BHGs), or formal forest certification programs (Biomass Research and Development Initiative (BRDI), 2009).

Logging residues can be derived from SRTS results by adding up those from growing stock removals in each survey unit by species. Further, these survey-unit level logging residues are the products of growing stock removals in SRTS result multiplied by residual factors by survey unit and species group from the TPO database. However, STRS does not allocate logging residues to regions. Nevertheless, it allows researchers to examine the supply of logging residues by species at the sub-regional scale.

SRTS results provide information on the location, species and type of logging residues. As can be seen in Figure 5.3, the primary source of logging residues resides in non-growing stock, both pine and hardwood. All four types of logging residues, pine and hardwood non-growing stock and growing stock, follows the same trend: a fall in the first few years followed by a bounce back and beyond 2007 levels. Additional regional information on logging residues by survey unit can be obtained in the STRS result file.

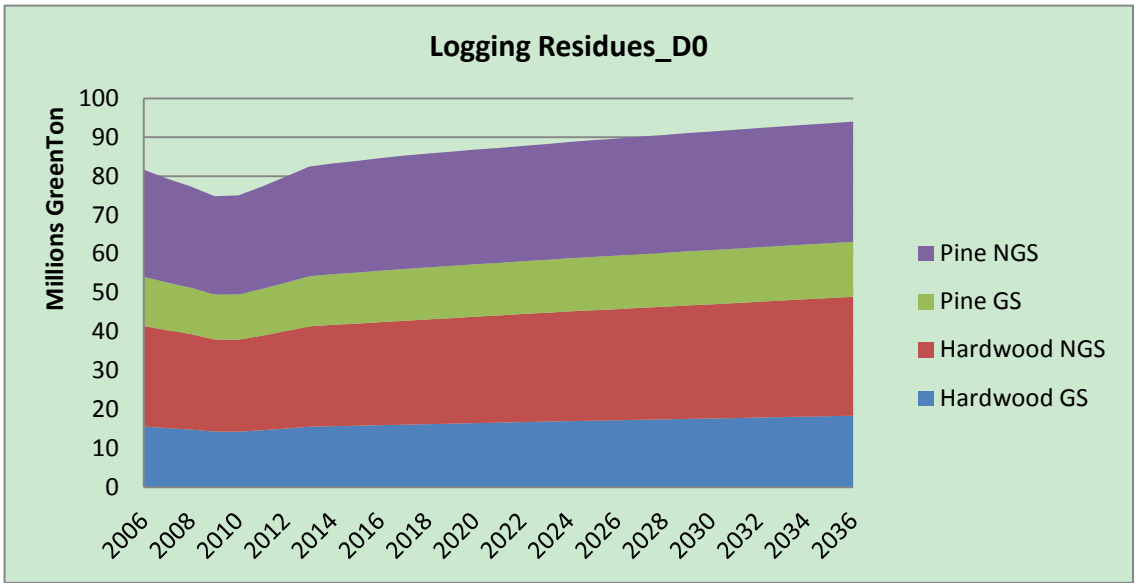


Figure 5.3 Logging residues by species under scenario D0

- Land use and management type change

The land-use change module is based on work by Hardie et al. (Hardie, Parks, Gottleib, & Wear, 2000; Hardie & Parks, 1997). The model allows for the land-use change due to urbanization and determines the shift between agricultural and forest land. Its underlying assumption about land-use change is that land for agriculture and forest is declining as a result of increasing demand for urban land resulting from a rising population.

Five forest management types are studied here, namely lowland hardwood, upland hardwood, mixed, natural pine, and planted pine. The underlying assumption is that the management type decision is made in order to lose fewer plantations as timberland declines or to gain more plantations as timberland increases (Abt et al., 2007).

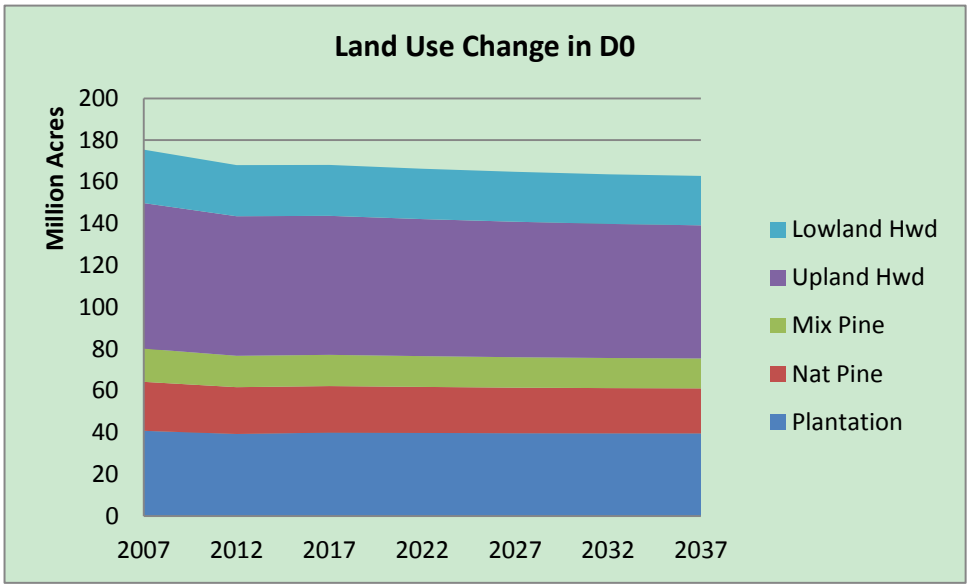


Figure 5.4 Forest land management type under Scenario D0

Results suggest that all management types of forest land are declining and thus so is the total timberland area, as a result of the economic recession and urbanization. The decline rate of each management type of land differs for the time period. Pine plantation has the lowest change rate, a 3% decline, while all other four types decline more than 7% in the 30 years period. Total timberland area drops by approximately 7%. The shift from forest land to agricultural or urban land can lead to job shifts to alternative sectors, carbon emissions from land conversion and habitat loss for wildlife in the forest.

Timberland loss over 30 years can also lead to changes in recreational, employment and community needs, land conditions and associated carbon emissions. One cannot equivocally state that the timber loss definitely brings about negative impacts. Rather, it can be assumed that such shifts give rise to changes not only in the forest sector but also

agricultural and urban sectors in social, economic and ecological aspects. The consequences can be negative, positive, or neutral depending on how the land use is conducted and where conversions move markets from and to.

Converting current land use can lead to complicated consequences on not only the forest sector. For instance, if agricultural land is converted to timberland, the area in question will run into a series of issues again, such as the competition of food vs. fuel, indirect land-use change, greenhouse gas release, nutrients and organic matter loss, and wildlife habitat loss. However, the scenario can be the opposite if forest land moves into marginal land. Afforestation and reforestation on marginal land is able to produce positive economic, environmental and ecological impacts. Forests improve productivity on marginal land, sequester more carbon in trees and soil, provide habitat for wildlife and protect the land from erosion. Furthermore, they bring income to local people by creating job opportunities. In other words, it can be very complicated to quantify the impacts associated with land-use change.

In addition, studies (National Research Council of the National Academies, 2007, 2008) have shown that intensified forest management gives rise to water quality concerns, and forest-based electricity facilities consume more water than coal generation plants, which might increase demands on local water supplies. In order to prevent these problems, complementary policies should be carefully designed and carried out. For instance, forest-based bioenergy facilities might not be established in places where water supply is scarce.

Therefore, the impacts are very site specific. They can be negative or positive, depending on the local condition, practice and technology.

- Forest age structure over time

The oldest age class (50+) of forest land accumulates and takes a bigger and bigger role over time, increasing from 30% to 43% of the entire forest. Also, the shares of age classes from 30-44 are rising as well while shares of other age classes decline from 2007 to 2037. Younger trees start to enter older age classes and they are not replanted or fully replaced in the time period. In the last few years of the period, over 40% of the forest is occupied by the oldest age class (50+), thus moving to an older age composition. Meanwhile, the forest area also declines in the entire time period, so the area of less than 30 years old age-classes is getting even smaller. A benefit of this shift is that old trees provide habitat for larger size wildlife, but at the same time the forest industry that utilizes younger trees is at risk and the age class structure is shifting away from its historically sustainable state.

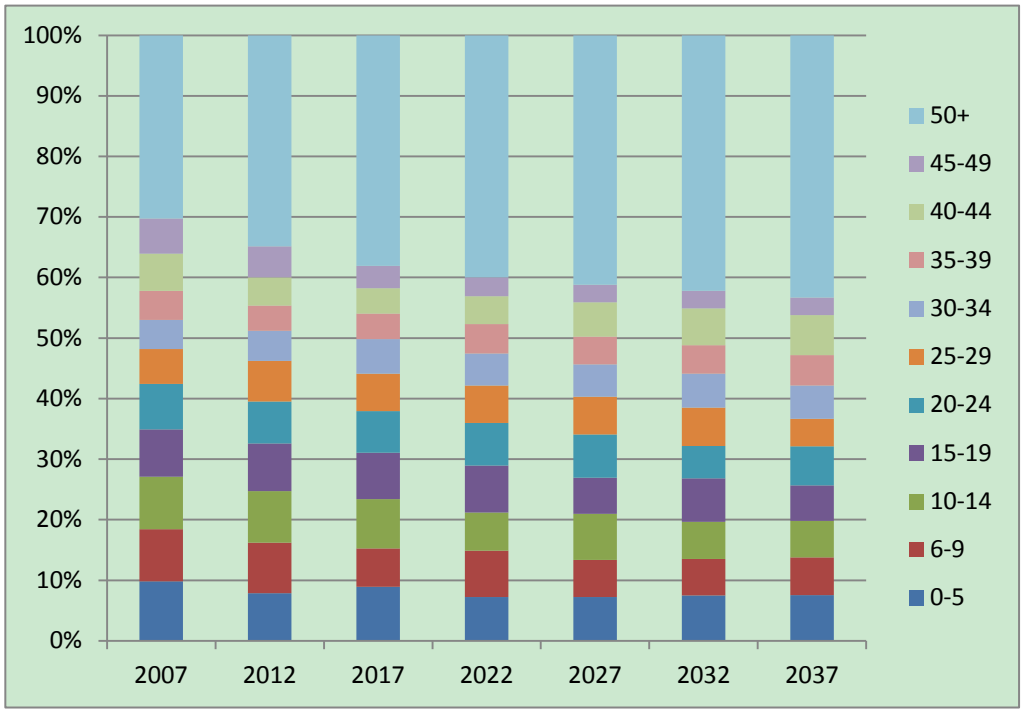


Figure 5.5 Forest age structure over time under scenario D0

5.2 EISA-RFS Scenarios

5.2.1 Baseline Scenario D1

In this scenario, pulpwood used for bioenergy production to meet EISA is added to SRTS for demand driven runs. Logging residues are assumed to be sufficient to provide all biomass needed, which is explained later in this sector.

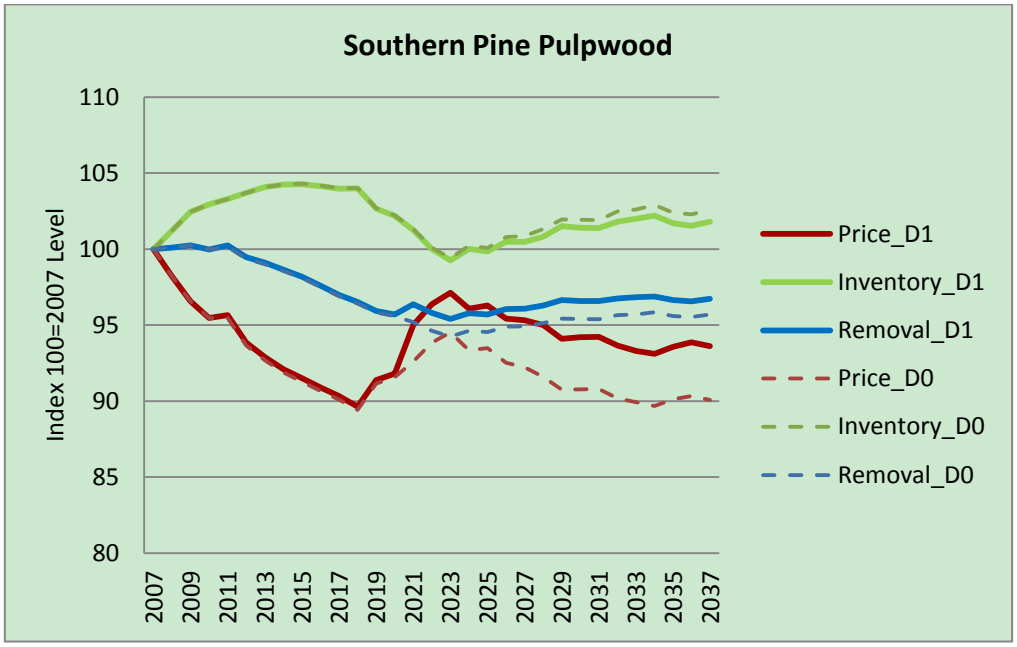
- Project market response

As can be seen from Figure 5.6, adding bioenergy-related demand for pulpwood boosts the pulpwood market by increasing product price and removals in the longer run, whereas it slightly reduces pine pulpwood inventory. Pine pulpwood price increases by 3.5 percentage

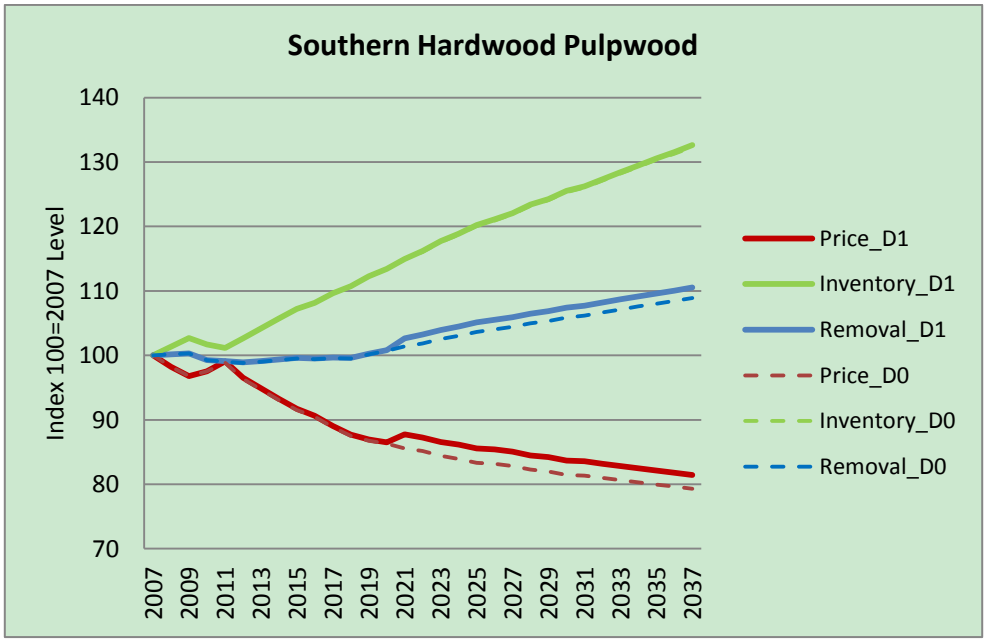
points in 2037 compared to Scenario D0, but still lower than its 2007 price level. The greater demand for pulpwood products provides economic incentives for land owners to harvest more pulpwood, but the industry still has an increasing inventory by 2037, although pine pulpwood inventory drops below 2007 level in 2023.

Additionally, since the SRTS model does not address cross-price substitution among the four products, there is no direct completion in the market of all forest products. Thus the figures of sawtimber products are not illustrated here. Nonetheless, the removal of pulpwood would reduce the future inventory of sawtimber in that the small trees wouldn't have the opportunity to grow into bigger trees.

Figure 5.6 Market Projection of Pulpwood Products under Scenario D1 (solid: D1; dash: D0)



(a) Southern pine pulpwood market response



(b) Southern hardwood pulpwood market response

Graphically, the regional change in inventory can be illustrated in the map below. Regional change in softwood pulpwood inventory varies greatly from state to state. NC, SC, FL, MS, LA, and OK experience a decline in softwood pulpwood inventory, with the largest decrease in SC: over 7 million tons. The biggest increase in inventory happens in AL: more than 19 million tons. Meanwhile, hardwood pulpwood inventory increases in all southern states, with the biggest rise in KY, followed by TN and GA. Compared with Scenario D0, hardwood pulpwood inventory for all southern states stays almost the same as before, but softwood pulpwood inventory in each state has an appreciable increase, some of which even turns negative to positive, such as AL, AR, GA, TN, TX, VA, and KY. Therefore, harvesting pulpwood for bioenergy actually raises inventory of softwood pulpwood but keeps that of hardwood pulpwood in all states but at different scale from 2007 to 2037.

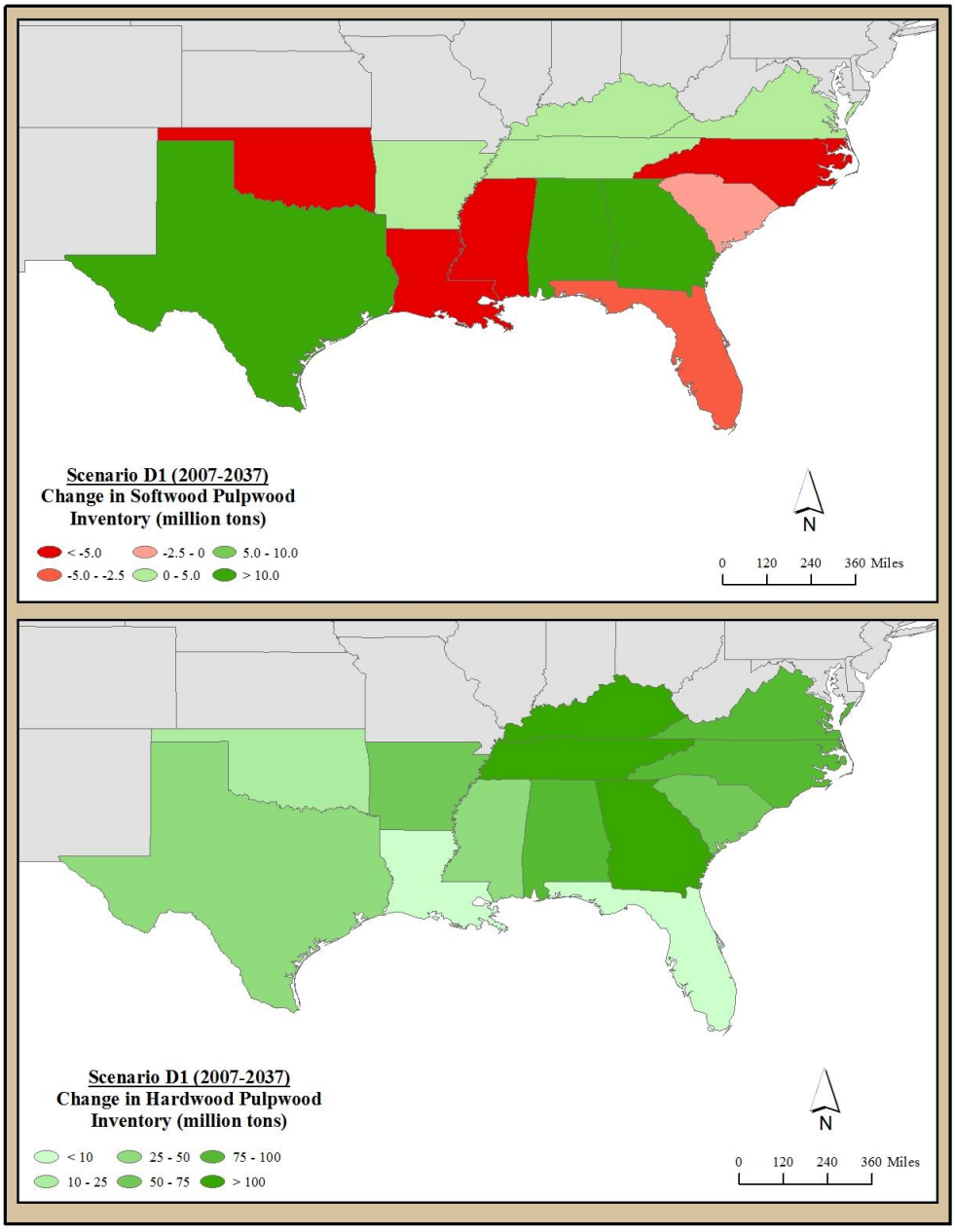


Figure 5.7 Maps of pulpwood inventory change by species and state in Scenario D1

- Displacement

Forest biomass supply comes from forest residues and forest products. An increase in bioenergy production's demand for forest biomass incentivizes more logging residue utilization and additional forest product harvest for bioenergy production. The source of forest feedstock can be disaggregated into (1) logging residues, (2) residues from increased harvest, (3) pulpwood displaced from traditional industry, and (4) increased pulpwood harvest. The first two are identified by SRTS directly and the last two are derived through side calculation based on SRTS output. If the bioenergy demand for pulpwood is at all price insensitive, the split between sources (3) and (4) can be easily obtained. Otherwise, the price elasticity is needed to separate the two. When the demand is perfectly price inelastic, pulpwood displaced from traditional industry and from increased harvest can be represented by their deviation from conventional industry without bioenergy demand for pulpwood. To be specific, the difference of the total pulpwood supply in Scenario D1 less that in Scenario D0 shows the increase in pulpwood harvest due to biofuel production-related demand. Furthermore, the total pulpwood supply net that used for bioenergy production is the pulpwood produced for traditional industry. Thus, the displaced pulpwood can be calculated by its difference from traditional used pulpwood in Scenario D0. This can be demonstrated graphically in Figure 5.8.

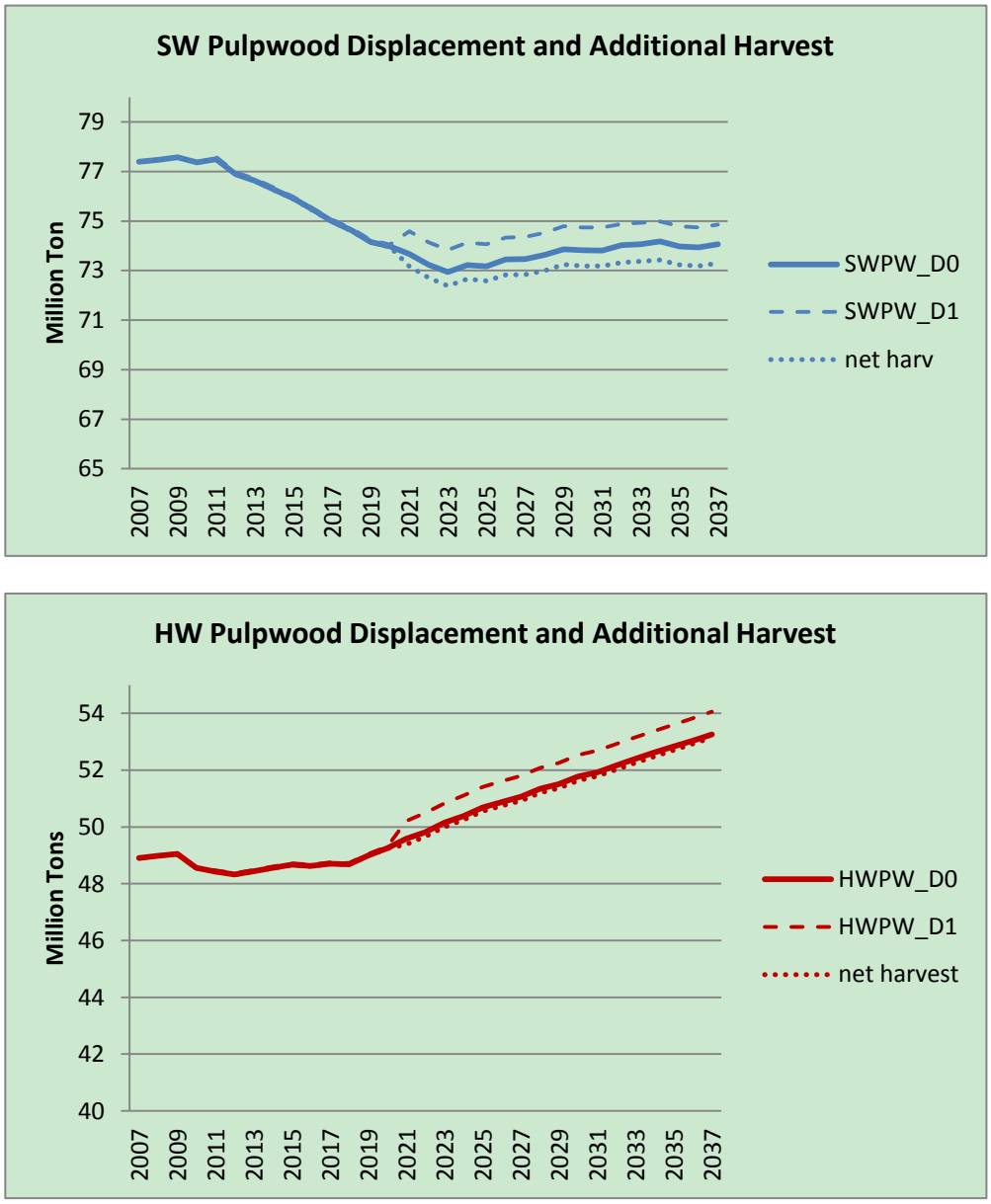


Figure 5.8 Pulpwood Displacement and Additional Harvesting under Scenario D1 (Elasticity=0)

In this scenario, the pulpwood has started to compete and displace some of the existing industry. Below figures separate the effects of additional harvesting and industry displacement for softwood pulpwood (in blue) and hardwood pulpwood (in red). The solid

line and big dash line denote pine and hardwood pulpwood harvests in the baseline scenario D0 and after adding the bio-demand, respectively. The distance between them represents the additional harvesting for pulpwood. The small dash line is obtained from the big dash net bio-demand for pulpwood, and its distance to the big dash line is the bio-demand for pulpwood. Thus, the displacement of traditional pulpwood industry is represented by the distance between solid line and small dash line, which is the difference between net harvest for the traditional pulpwood industry in scenario D1 and the baseline scenario D0. From the two figures, the displacement from softwood pulpwood looks larger than from hardwood pulpwood for most of the time. Altogether the displacement ranges from 0 to 0.9 million tons. Thus, in the long run, less than 1 million tons of feedstock for the pulpwood industry is displaced by the bioenergy industry by 2037.

However, it is noticeable that the inelasticity assumption implies that the industrial demand for pulpwood stays the same regardless of the price change, which might not be valid for greater price changes and/or longer time period. Nevertheless, given empirical price elasticity of bioenergy demand for pulpwood, a more realistic industrial displacement can be derived. In order to show the influence on the result, I take -2 and then -0.5 as the price elasticity for example. When pulpwood price goes up by 1%, bioenergy demand for pulpwood falls by 2% or 0.5% and thus the displacement from industry is smaller than in zero elasticity case, which can be represented by the distance from the solid blue line to the solid purple line in the two figures below. It can be observed that the more elastic the bioenergy demand is, the smaller industry displacement takes place. Particularly for

softwood pulpwood, when elasticity changes from -2 to -0.5, the industry displacement increases about 0.09 million tons by year 2037. Similarly, the displacement increases another 0.03 million tons in the same year when elasticity drops from -0.5 to zero, as shown by the dotted line. Therefore, the price elasticity has a relatively large impact on the industry displacement, but since there is insufficient empirical data to estimate it, zero price elasticity is adopted to represent an upper bound for the displacement for the following scenarios.

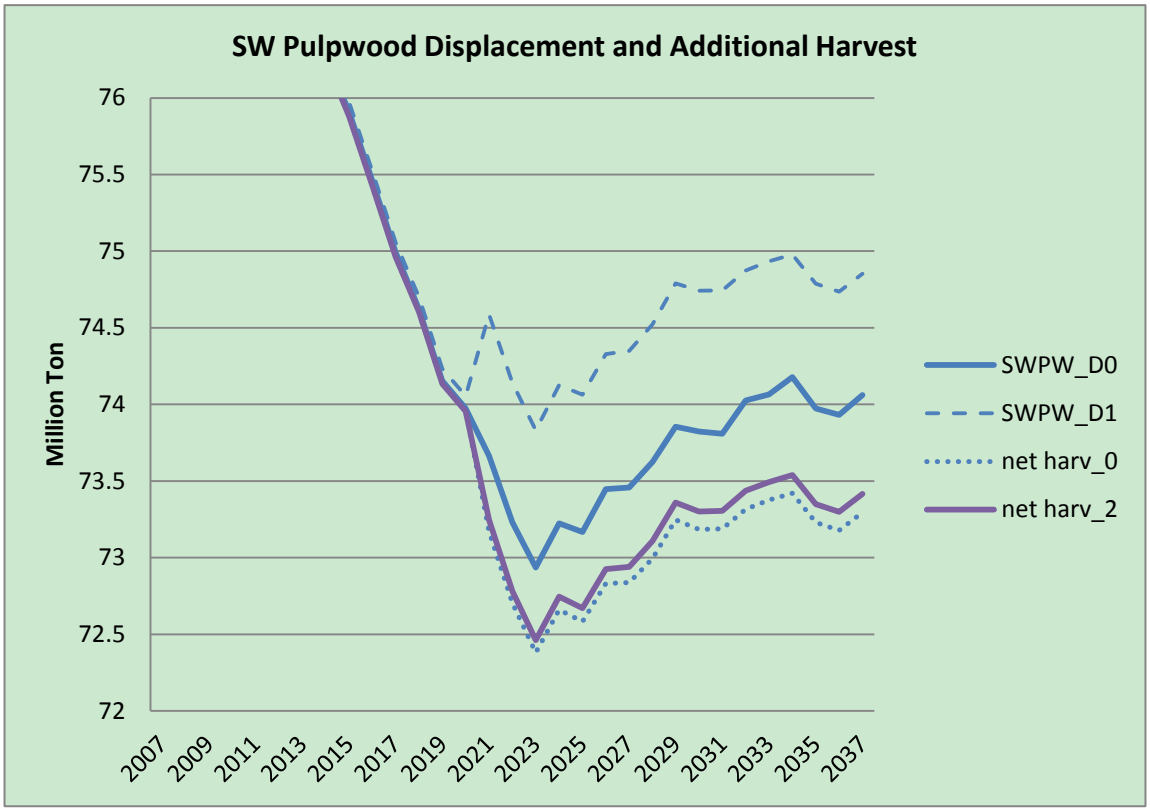


Figure 5.9 Pulpwood Displacement and Additional Harvesting under Scenario D1 (Elasticity=-2)

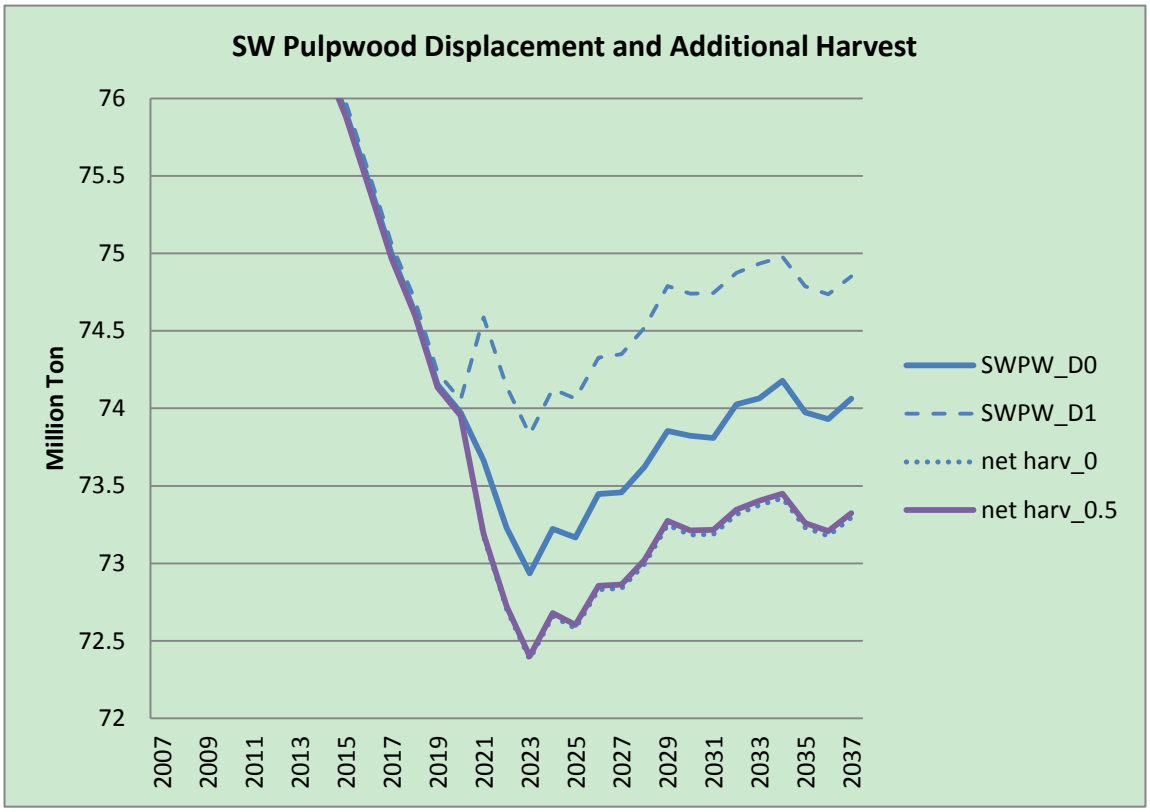


Figure 5.10 Pulpwood Displacement and Additional Harvesting under Scenario D1 (Elasticity=-0.5)

- Logging residues

Compared to baseline 0, more logging residues are produced each year, due to the increased removals in both hardwood and softwood. However, the increase rate is very small, less than 1%. Softwood has an even smaller increase rate than hardwood in logging residue generation. Moreover, the hardwood pulpwood already plays a slightly larger role in the logging residue quantity in Scenario D0, not to mention the bigger rise after adding the bioenergy demand for pulpwood. The logging residue by type figure is similar to scenario D0, as illustrated in Appendix B.

The following figure illustrates the minimal utilization rate that must be achieved to meet the RFS demand each year. As can be seen, logging residues removal rate ranges from approximately 42% to 49%, which falls into the range used by Perlack et al. (2005), which assumes that at least 30% of the total logging residue has to be left on the ground for sustainability purposes. The removal rate/utilization rate for sustainability purposes differs from site to site. As described earlier, it depends on slope, soil conditions, and other factors. Perlack (2005) indicated that, in general, retaining 30% of logging residues on slopes less than 30% and 50% on steeper slopes are reasonable estimates for sustainable purposes. Removing too much would lead to severe nutrition loss in the soil, water and wildlife habitat loss. Thus, this range of utilization rate is not unrealistic, given the high removal rate that can be achieved in the Southeastern states. Nonetheless, a sensitivity analysis on this utilization rate is conducted later in Scenario 5, with a maximum removal rate of 25% for all southeastern states.

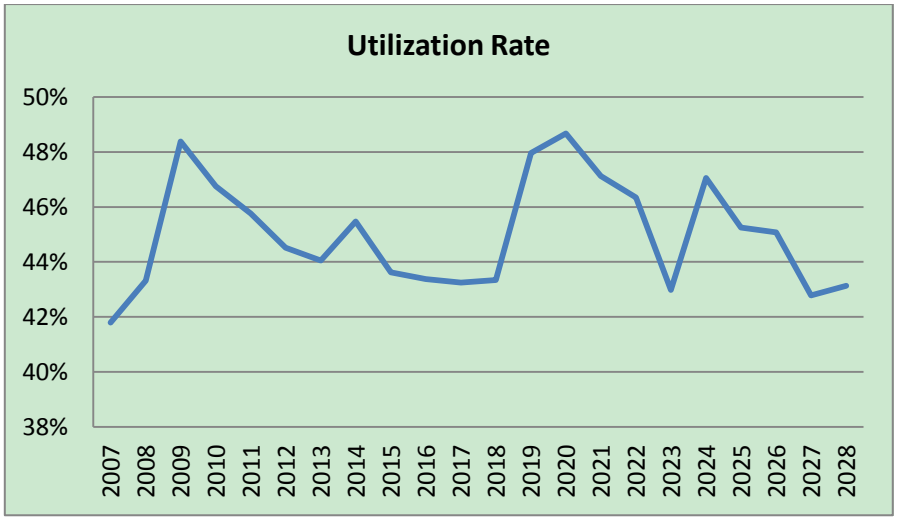


Figure 5.11 Logging Residue Utilization Rate under RFS Scenario D1

At a 50% utilization rate, the logging residues are able to meet the RFS2 biofuel mandates and electricity demand at the same time. However, it is not clear which is prioritized by logging residue: biofuel or electricity. This is because POLYSYS does not address the choice between producing biofuel or power. Rather it deals with the question of how much resource is needed to meet the mandates.

When utilization rate is reduced to 25%, there is not enough logging residue for each year. In this case, alternative woody biomass sources are considered. In the short term, when we run out of the low-value biomass, the conventionally sourced wood, i.e. pulpwood-sized roundwood, comes into play as a source for bioenergy. In order to examine the impact of logging residue removal on the existing forest market, a scenario of 25% utilization rate is discussed in the next section.

- Land use and management type change

The forest management type in Scenario D1 follows a similar pattern as in D0. Plantation area in this scenario declines by 2.8%, whereas the other four management types of land, lowland and upland hardwood, mixed pine and natural pine, are all dropping at a more than 7% rate. However, due to the bioenergy demand for pulpwood, this scenario loses less land each year, but to a very small extent, around 0.1% more timberland than scenario D0. The decrease in land loss is attributable to a higher pulpwood price in the market, which creates more economic incentive to keep forest land. Nevertheless, the timberland area still falls below 2007 levels in the end of the period, in that the land-use change is more closely

tied to the higher value product sawtimber. Therefore, with bioenergy production demand for pulpwood, more timberland is retained, and so are the ecosystem services associated with it.

- Forest Age Structure over time

Under both scenarios, trees under 30 years old are fewer over time, whereas more trees enter the 30-34, 40-44, and over-50 age classes. Thus, generally the age structure is moving to an older composition. Compared to Scenario D0, more trees under 15 years old and above 50 years old are planted or maintained despite of the downward trend, and trees at other age classes are fewer at least for some of the years covered by the model. Age classes between 15 to 49 years account for 42.7% of all classes in 2007 but drop to 36% in 2037 in Scenario D1 and to 37% in Scenario D0. This loss of age classes is likely to cause negative impacts on timber products, biodiversity, and forest integrity.

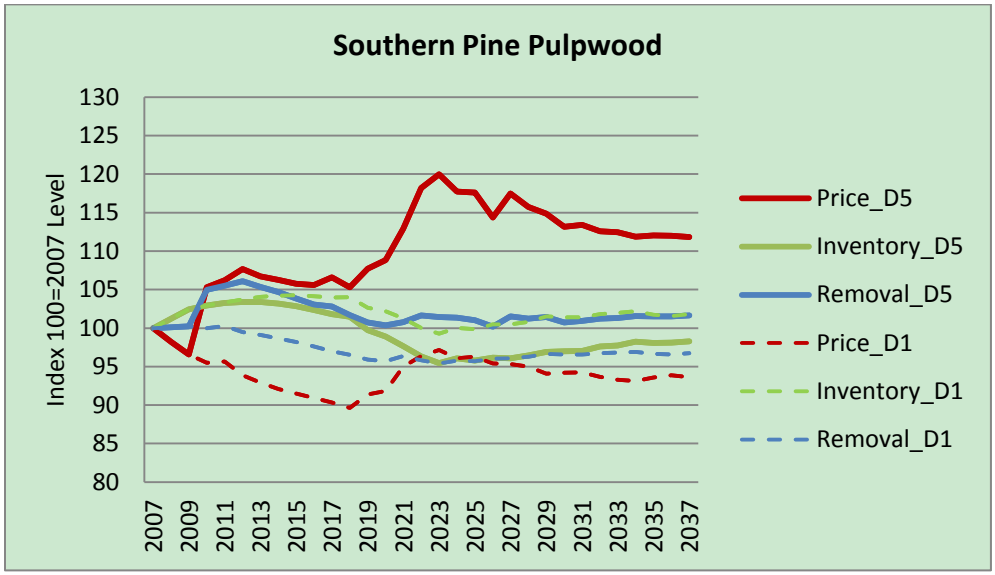
5.2.2 25% Residue Utilization Rate (Scenario D5)

If only 25% of total logging residues are allowed to be removed, the gap in bio-demand is assumed to be met by pulpwood.

- Market response

Due to lack of sufficient logging residues for biofuel production, the pine pulpwood market is significantly impacted by this surplus demand. As can be seen in the figure, the pine pulpwood price bounces back to the 2007 level in less than 3 years and then keeps above this level for the rest of the time period. It peaks in 2023 with a 20% increase and levels off at 12% higher than 2007 price level. The hardwood pulpwood price has a boost as

well but at a smaller scale. It approaches a 10% increase in year 2013 but still falls 7% below that of the 2007 level in 2037.



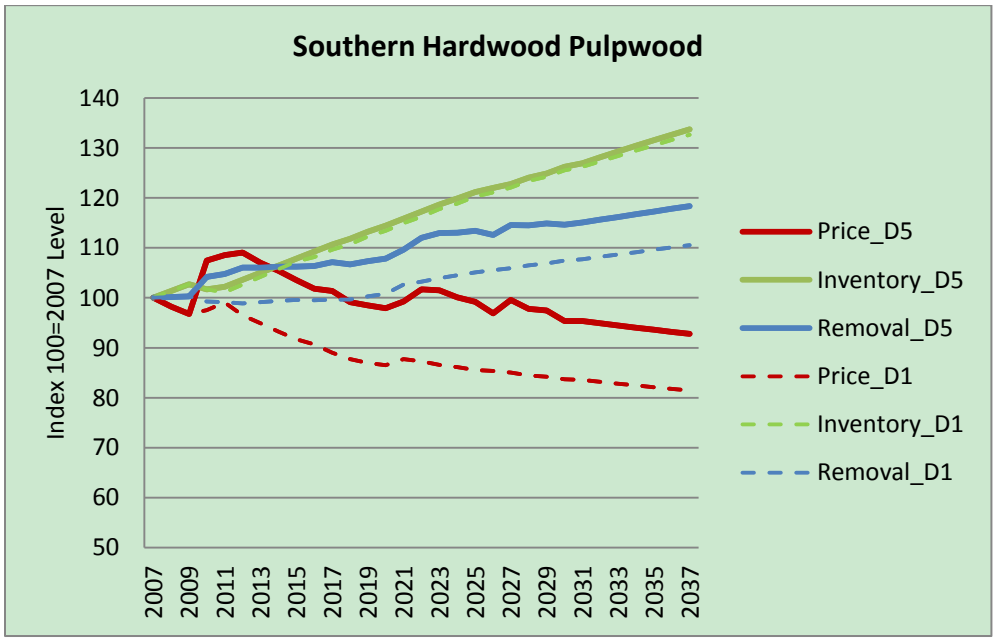


Figure 5.12 Market Projection of Pulpwood Products under Scenario D5 (solid: D5; dash: RFS D1)

This incremental demand for pulpwood for bioenergy production helps the forest market to bounce back from recession quickly and pushes the equilibrium to the right with a higher supply and price level. This explains the increased removal in both pine and hardwood pulpwood markets. However, different from hardwood pulpwood removal, which falls below the inventory curve from year 2013, pine pulpwood removal exceeds its inventory level as early as around 2010. Thus, the pine pulpwood inventory falls under the 2007 level starting in year 2019, and the hardwood pulpwood inventory increases over time. This signifies a less abundant pine pulpwood inventory and likely leads to a deficit of its future supply and price spikes. In the short/medium run, the pulpwood cannot grow as much as removals require, so the forest resource would likely be intensively harvested and/or potentially expanded onto other land by converting current land use regionally.

Compared with Scenario D1, the change in pine pulpwood inventory in each of the southeastern states is smaller, while the change in hardwood pulpwood inventory is smaller in some states and larger in the other. Due to the smaller change in pine pulpwood inventory, AR and VA change from inventory growing states back to inventory decreasing states, from Scenario D1 to D5. This is attributable to the rise in pine pulpwood price and removal, which leads to a reduction in inventory.

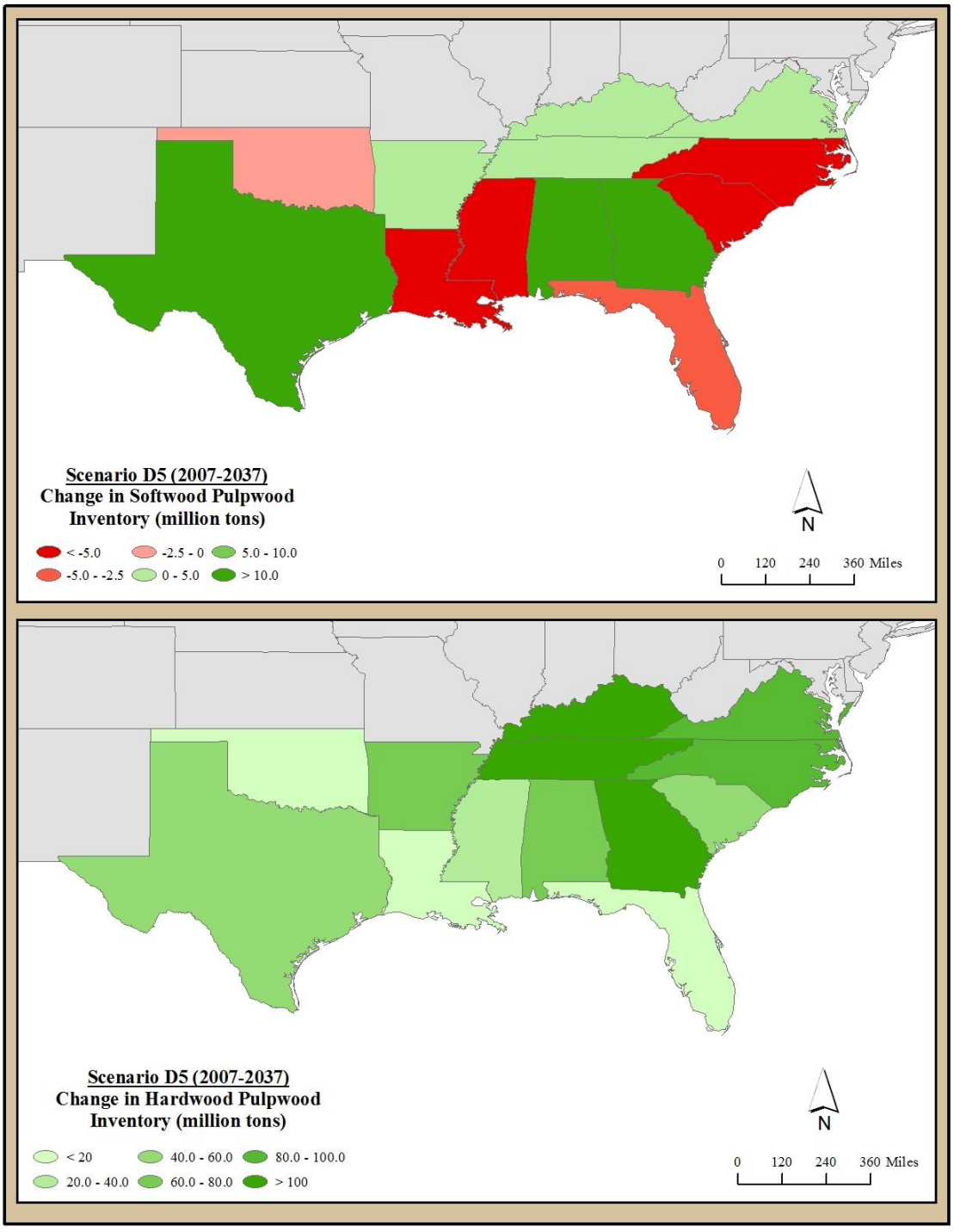


Figure 5.13 Maps of pulpwood inventory change by species and state in Scenario D5

• Displacement

As described in the baseline scenario, the figure below shows the additional harvesting for pulpwood and the displacement from traditional pulpwood industry, denoted by the distance from solid line to small dash line, given zero price elasticity for bioenergy demand. It can be seen that both additional harvest and displacement from traditional pulpwood industry are quite large, approximately 8 million tons from industry displacement and 10 million tons from additional harvest in some years for both species combined. The large quantity of additional harvest and displacement in the longer run is likely to result in forest product price and inventory change, as illustrated earlier, biodiversity loss, and forest land use change.

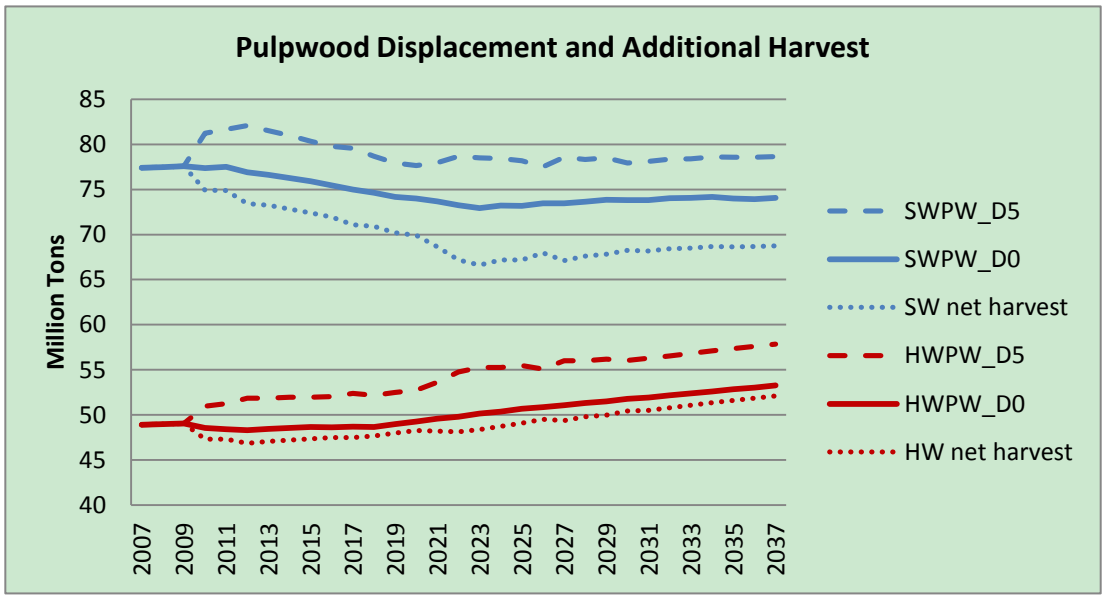


Figure 5.14 Pulpwood Displacement and Additional Harvesting under RFS scenario D5

- Logging residues

The available logging residues are expected to be greater than those in Scenario D1 for most of the years covered by the model, due to the big rise in pulpwood demand and removal. The increase rate peaks in year 2011, when approximately 3.5% more logging residues become available. Same as before, hardwood logging residues are greater in both quantity and increase rate for each year than softwood. Thus, the average increase rate for both species of the entire period only rises by 2.4% beyond Scenario D1. This is still not a big change in logging residue quantity, so the lag in demand for woody biomass would be satisfied to a large degree by pulpwood. In other words, there is little room for logging residues to contribute significantly beyond RFS Scenario D1. Nevertheless, in this scenario, a much smaller amount of logging residues is removed, so more wildlife habitat is preserved, and soil nutrients are maintained.

- Land use and management type change

The much higher price of wooded acreage provides large incentives for landowners to maintain timberland, so an approximately 1% increase is observed for each management type of timberland, compared to Scenario D1, and thereby a smaller loss in total area. The average land reduction rate for each management type is smaller than before and thus the average timberland loss rate falls to 5% in D5 compared to 7% in D1 for the same 30 years. However, this increase is still not big enough to reverse the declining trend of timberland area, primarily resulting from urbanization and conversion to agricultural activities.

- Forest Age Structure over time

There are many more acres for young trees under 20 years old and old trees above 50 years old, compared to Scenario D1, while the age classes between 20 to 50 years have smaller acreages in this case. The higher pulpwood demand incentivizes land owners to plant seedlings more densely and harvest them for pulpwood. So as time goes on, the age class 20-49 is shrinking due to the additional harvest of younger trees that could have grown into this age class. Thus, the age class structure is turning more bimodal, with a bigger share of young and old trees. The trees aged from 20 to 49 become less important in the forest, which leads to a possible loss in future sawtimber product supply and biodiversity.

5.3 Corn ethanol subsidy removal scenario (D2)

Imposing this policy shock to MFM model produces adjustments in total biofuel, feedstocks and their respective biofuel markets. The results are shown in Table A.11 in appendix A. In this case, when the corn ethanol price goes up by 23.8% due to the subsidy removal, the total ethanol price rises by 11%. Other types of ethanol remain at the same price but all increase in quantity by 7.6%, which results from the higher price and thus reduce quantity in corn ethanol by 7.3%. Also, the other biofuels grow along with the increase in their input factors. So the new demand for woody biomass is approximately 7.6% more than that in D1. The present study assumes that this rate applies to all sources within the woody biomass group. In addition, given that the corn price is not changed, the agricultural price schedule is kept the same as before.

- Market responses:

Compared to scenario D1, as a result of the tax credit removal, there is around 7.6% more demand for pulpwood. So we expect to observe the price and removal of pulpwood shifting upward, while its inventory shifts downward. More pulpwood is harvested, resulting in a smaller forest inventory than that of scenario D1. However, the price, inventory, and removal schedules of pulpwood products are almost identical to Scenario D1, with slightly higher price and removal levels, at a scale of less than 0.5 percentage points. The change in inventory is even smaller, with gains and losses in different years. The decrease in pine pulpwood inventory is attributable to the decline in timberland acres, which is shown later. Thus, the removal of corn tax credit on top of EISA has very limited impacts on the pulpwood market and forest inventory. Therefore, the forest product future supply in a corn ethanol subsidy removal scenario should be almost the same as those in Scenario D1.

- Displacement

With zero price elasticity, industry displacement and additional harvesting under this scenario are both very small, ranging from 0 to 0.7 million tons. However, it is unexpected that pulpwood displacement from industry will be smaller than that in D1, especially for hardwood pulpwood, whereas additional harvest is larger than that of D1. Therefore, the removal of corn tax credits beyond RFS leads to a decrease in industry displacement yet an increase in additional harvest. This explains the negligible change in pulpwood price and the decrease in timberland area, which will be shown later, beyond those in D1. Thus, the pulpwood industry is less influenced by tax credit removal than harvesting and its associated

forest land use change. The regional inventory change maps by species are shown in Appendix B. Some states have a bigger change in pulpwood inventory and the others are smaller, compared to the inventory changes in Scenario D1.

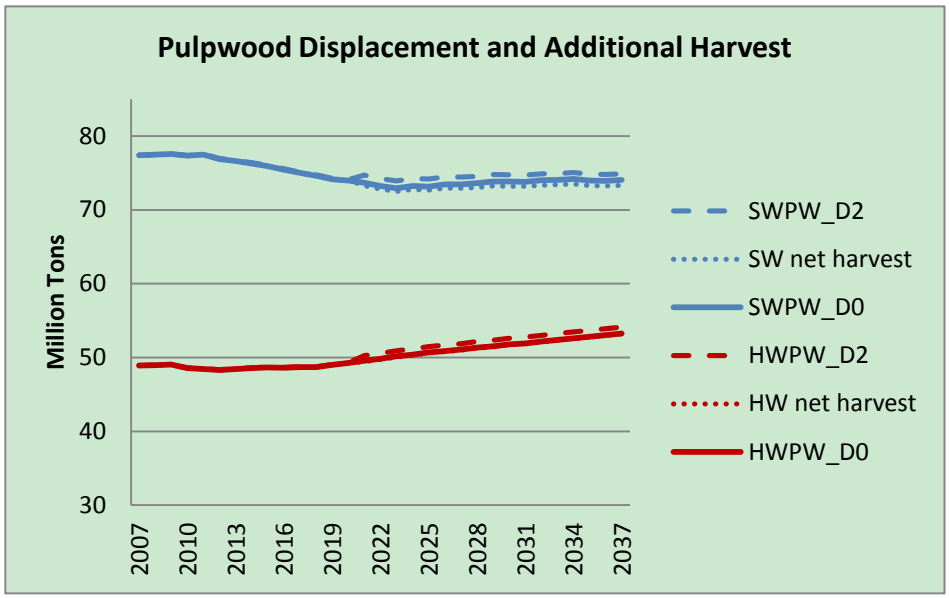


Figure 5.15 Pulpwood Displacement and Additional Harvesting under Scenario D2

- Logging residues

More hardwood logging residues are generated than are in Scenario D1, whereas softwood logging residues are the opposite for most of the time. The hardwood logging residue has its biggest increase, 0.07%, from D1 to D2 in year 2022, while softwood logging residue falls by 0.13% in 2037. As can be observed, the change rate from D1 to D2 is very limited and marked by the opposite kind of change for different species. Thus, the role of hardwood gets bigger in total logging residues, and the utilization rate barely changes.

- Land use and management type change

As before, each management type of timberland displays a declining trend over time, among which plantation has the smallest decrease rate: about 3% for the time period, while other four types decline more than 7%. Compared to scenario D1, all forest land use types decrease a little further in acreage, except for upland hardwood which does not fall beyond Scenario D1. The total area of forest land decreases by 7% on average over time and declines further by 0.01% of Scenario D1's baseline decrease, as a result of the corn tax credit removal beyond RFS. Thus, the increased demand for pulpwood due to tax credit removal leads to a further decrease in plantation or natural pine area beyond those in D1. This scenario brings about possible losses in forest land biodiversity, and related wildlife habitat.

- Forest Age Structure over time

As before, the acres of trees under 30 and age classes 35 to 39, and 45 to 49 decline for the time period, while the acres of mid-aged (30-44) trees have up and downs. The only all-time increasing age class is the oldest, over 50 years age class. The age-class change from scenario D1 to this one is very mixed, too. The area of some age classes is larger in some years, but smaller in other years. Overall, the age classes 0-5, 10-14, and 40-44 are slightly larger (less than 0.1%) than those in scenario D1, while the grand total is 0.01% less. Thus, the decrease in mid-aged tree classes has the potential to impact the timber market in the future, and the decrease may also influence forest integrity and health.

5.4 Demand Pattern Change Scenario (Scenario D4)

Table 7 MFM Results on Demand Change for Feedstock under AEO Projection (Unit: %)

	Corn	Stover	Switchgrass	poplar	Wood	other
2009	15.586				15.586	15.586
2010	14.713				14.713	
2011	17.923	17.923	17.923		17.923	17.923
2012	17.528	17.528	17.528		17.528	17.528
2013	12.529	12.529	12.529		12.529	12.529
2014	7.839	7.839	7.839		7.839	7.839
2015	-0.98	-0.98	-0.98		-0.98	-0.98
2016	-4.436	-4.436	-4.436		-4.436	-4.436
2017	-7.79	-7.79	-7.79		7.79	-7.79
2018	-11.615	-11.615	-11.615	-11.615	-11.615	-11.615
2019	-15.666	-15.666	-15.666	-15.666	-15.666	-15.666
2020	-18.362	-18.362	-18.362	-18.362	-18.362	-18.362
2021	-22.874	-22.874	-22.874	-22.874	-22.874	-22.874
2022	-26.899	-26.899	-26.899	-26.899	-26.899	-26.899
2023	-23.186	-23.186	-23.186	-23.186	-23.186	-23.186
2024	-19.504	-19.504	-19.504	-19.504	-19.504	-19.504
2025	-15.498	-15.498	-15.498	-15.498	-15.498	-15.498
2026	-11.771	-11.771	-11.771	-11.771	-11.771	-11.771
2027	-8.116	-8.116	-8.116	-8.116	-8.116	-8.116
2028	-4.41	-4.41	-4.41	-4.41	-4.41	-4.41
2029	-0.714	-0.714	-0.714	-0.714	-0.714	-0.714
2030	3.272	3.272	3.272	3.272	3.272	3.272

Each item responds to a proportional change in feedstock input, which is negative for each feedstock under AEO projections from 2015 till 2029. The numbers represent the adjustment in feedstock quantities to those of Scenario D1. The adjustment from the AEO to RFS scenario in terms of wood demand is positive for the first 6 years and then negative until year 2029. As described in the scenario construction, biofuel production is assumed to be the

same for the seven years after 2030. Thus the percent change in feedstock demand from D1 to D4 is kept the same as in year 2030, which is 3.27%. Overall, the total bioenergy demand for pulpwood for all years is about 2.7% less in Scenario D4, which is too small to observe in the figure below.

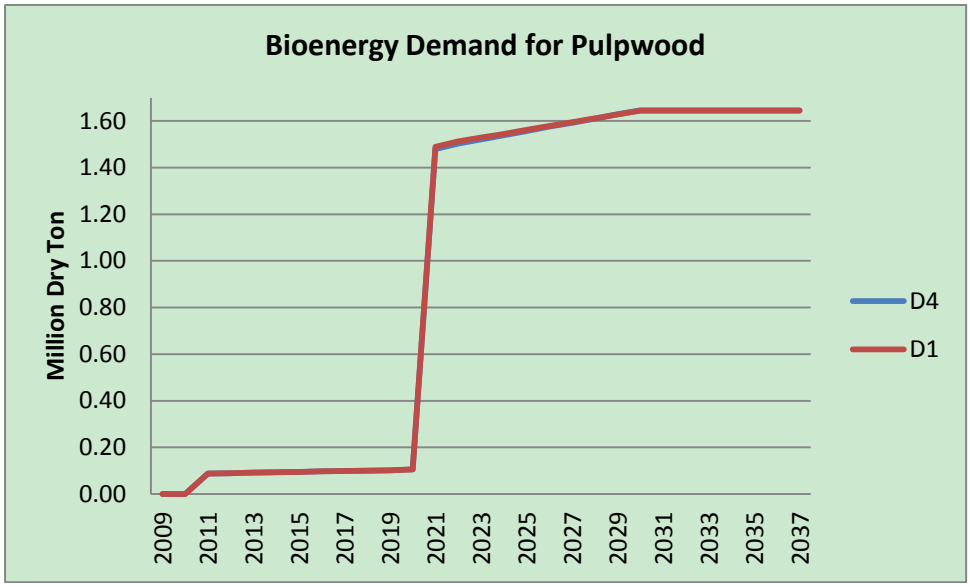


Figure 5.16 Bio-demand for Pulpwood under D1 and D4

- Market response

As can be observed in the figure below, the market response of hardwood pulpwood in this scenario is almost identical to scenario D1. However, compared to scenario D1, the price and removal levels of pine pulpwood are lower for most of the time and higher for the rest, whereas the inventory is the opposite. Pine pulpwood is clearly more sensitive than hardwood pulpwood to demand change. The difference in biofuel production schedule and quantity leads to the difference in pine pulpwood market response. Both scenarios are able to meet the biofuel mandate by 2030, but the price and removal levels in D4 are slightly lower

than those in D1 for most of the years. The new schedule thus gives more time for the bioenergy industry to develop and for the existing pulpwood industry to make adjustments.

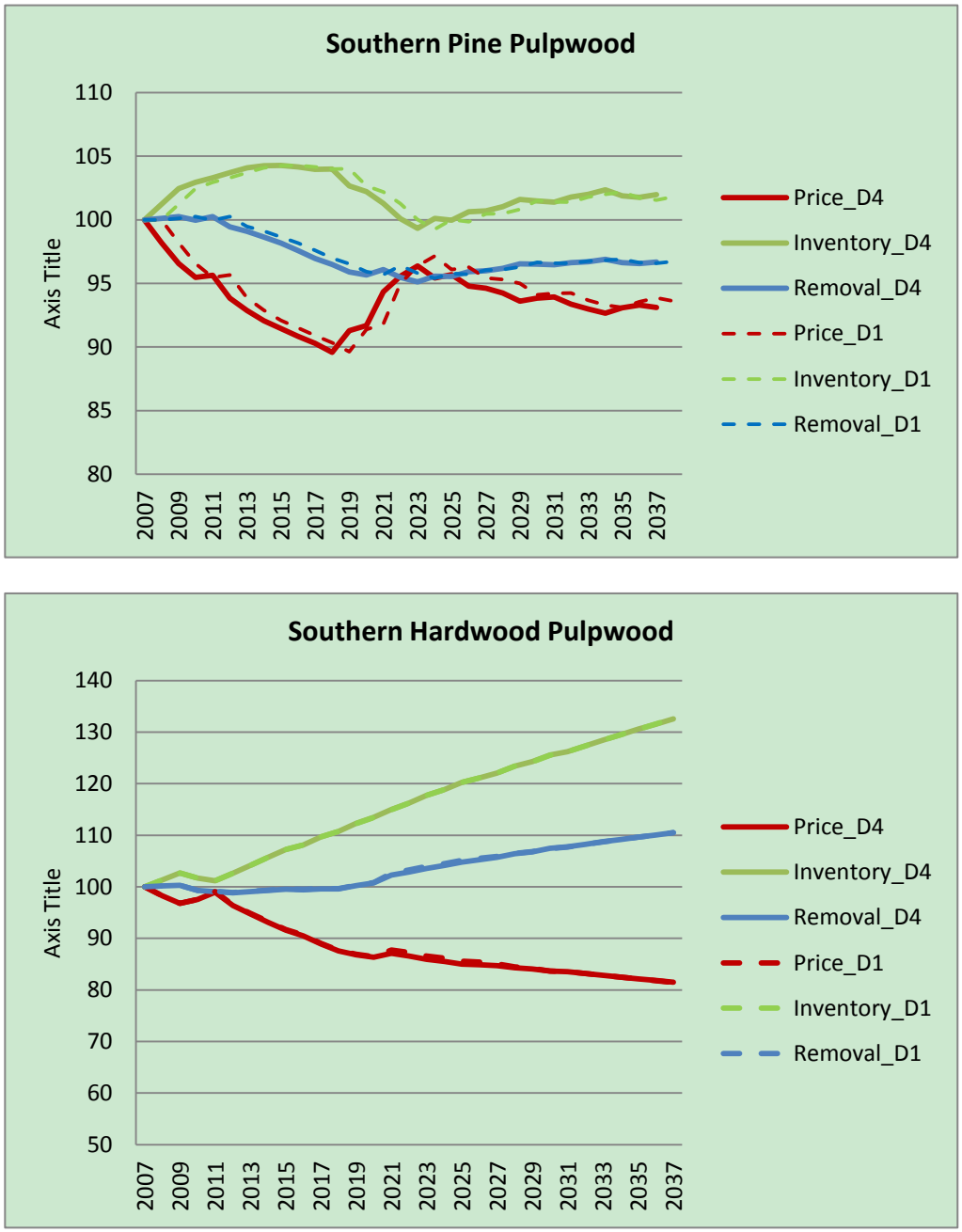


Figure 5.17 Market Projection of Pulpwood Products under Scenario D4 (dash: D1; solid: D4)

- Displacement

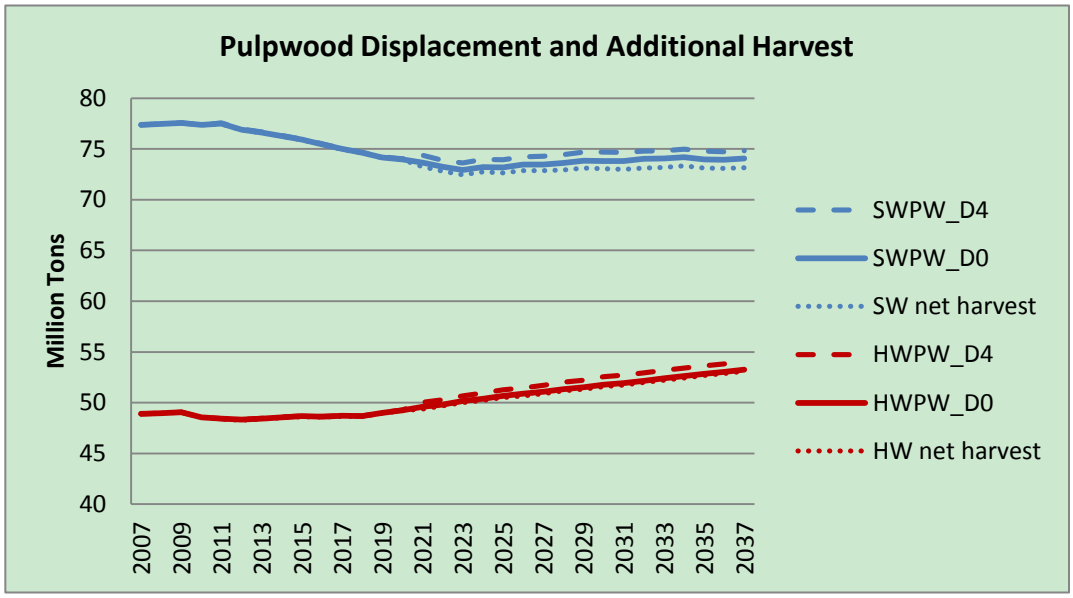


Figure 5.18 Pulpwood Displacement and Additional Harvesting under Scenario D4

The displacement is still very small with zero price elasticity under this scenario. Compared with scenario D1, the pulpwood displacement seen here is slightly greater in the beginning (less than 0.06 million tons) and towards end of the period (around 0.2 million tons) but smaller for a few years in the middle (less than 0.1 million tons). Meanwhile, additional harvesting is less than that of D1. Therefore, pulpwood for bioenergy demand displaces more from conventional industry than it does in scenario D1, but expands less harvesting for all years. Thus, the new demand pattern strengths industry displacement but weakens additional harvesting, which is opposite from the impacts of the corn tax credit removal scenario.

- Logging residue

The quantity of logging residues from both species are declining each year compared to those in D1. In particular, hardwood logging residue quantity falls at a faster rate and to a greater degree than that of softwood logging residues. The biggest decline in hardwood logging residues happens in 2022, approximately 0.22%, compared to a 0.12% decline for softwood logging residues in the same year. Thus the larger decrease in hardwood undermines the role of hardwood in total logging residues quantity, but at a very small scale. Therefore, the utilization rate of logging residues becomes slightly larger, less than 0.01% at the most.

- Land use and management type change

All of the five management types of forest land decline below the 2007 level, whereas plantation goes up from 2011 to 2021 despite of its overall declining trend. The forest land has its biggest loss in mixed pine (10%) and smallest in plantation (2.8%). However, when this scenario is compared to Scenario D1, the area loss in natural pine, plantation, mixed pine and upland hardwood is larger, while the loss in lowland hardwood is smaller. Thus, the total timberland area is around 0.02% less in Scenario D4 than that in D1. Pushing the mandates to future years brings about a greater loss in timberland acreage.

- Forest Age Structure over time

The pattern seen here is similar to other scenarios. The share of trees younger than 30 shrinks and that of age classes 30-34, 40-44, and above 50 expands. Compared with Scenario D1, overall there are more acres in age classes 10-29, but less in the others. The shift

represents an increase in the age classes that experience reduction in Scenario D1 and a decrease in the classes that are expanding in D1. Thus, this scenario can be seen as an attempt to contradict the effect of RFS mandates in D1, but to a very small degree. In this sense, this demand pattern is more sustainable than RFS scenario D1 in terms of restoring forest age class to its historic levels.

5.5 Technology Change Scenario (Scenario D3)

When a 25% cost reduction is imposed on wood-based ethanol, we can expect a 17.82% rise in its quantity due to a corresponding rise in wood feedstock input. In Scenario D3, other biofuels decrease in their quantity and their demand for feedstock quantity by 3.67%, causing the ethanol price to decrease by 5.2%. As before, the study assumes pulpwood used for bioenergy production goes up by the same amount as 17.82% by 2022.

- Market responses

The pulpwood market under technology improvement parameter is very similar to the same market in scenario D1, as illustrated in the Appendix B. The price and inventory of pine pulpwood are slightly higher than those in D1, at the scale of less than 0.7 percentage points, whereas the inventory falls a little bit. However, the removal, inventory and price of hardwood pulpwood are all higher after the technology change, although to a very small extent, approximately 0.3 percentage points at most. Therefore, the technology improvement in wood-based biofuel production saves cost by 25% and increases the pulpwood demand by 11.7% beyond RFS scenario D1, which leads to a less than 1% rise in price and removal.

Meanwhile, hardwood pulpwood price, inventory, and removal levels surpass those of scenario D1, which is beneficial to maintaining a sustainable forest supply for the industry.

- Displacement

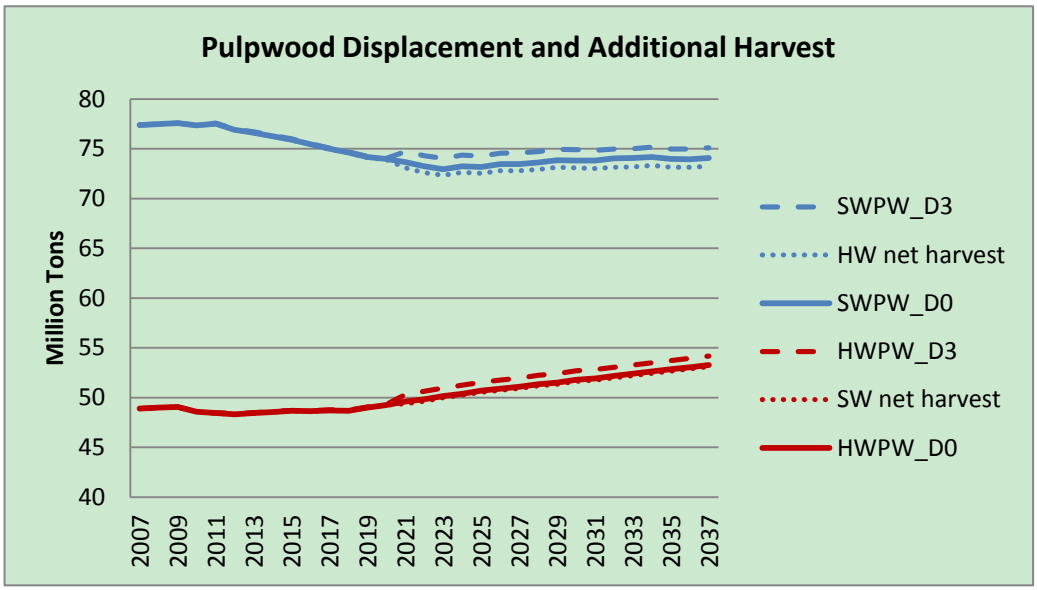


Figure 5.19 Pulpwood Displacement and Additional Harvesting under Scenario D3

Given zero price elasticity, the displacement from the pulpwood industry is around 0.8 million tons of softwood pulpwood and 0.15 million tons of hardwood pulpwood by 2037. The additional harvesting is approximately at the magnitude of 1 million tons for either softwood or hardwood pulpwood. Both of displacement and additional harvesting in this scenario are larger than those in D1. Thus, according to this model, a major advancement in wood-based biofuel technology makes it economically feasible to use more pulpwood for bioenergy through both additional harvesting and displacement from conventional industry.

- Logging residues

Looking at the residue composition from 2007 to 2037, hardwood non-growing stock grows faster than others, followed by hardwood growing stock. Compared with scenario D1, this higher bioenergy demand for pulpwood encourages the use of more logging residues from both softwood and hardwood. The increase rate from D1 to D3 for hardwood peaks in 2022 at 0.11% and for softwood in 2022 at 0.11%, as well. Different from previous scenarios, the increase rate for softwood logging residue is larger than that of hardwood, which represents a slightly bigger role in increased logging residues from softwood. Due to the small rise in logging residues, there is little decrease in utilization rate needed to meet the demand.

- Land use and management type change

Still, all management types of timberland decrease in this scenario. Among them, plantation has the least loss, around 3% for the 30 years, while others lose more than 7% in the same time period. As expected, because of the economic incentive to keep forestland, there is less timberland loss in each of the five management types of forest land, compared to scenario D1. Thus, the combination of land is shifting towards plantation, which potentially impacts biodiversity. However, this incentive is not strong enough to reverse the downward sawtimber market or dominate the forest land change decision. Overall, the forestland in Scenario D3 is around 0.03% larger than that of D1.

Forest Age Structure has a similar pattern to other scenarios. The shares of trees under 15 and above 50 yrs old are bigger than those in scenario D1. So the technology-induced

biofuel producing demand for pulpwood encourages harvesting and planting more pulpwood and thus losing some of the mid-age trees.

5.6 Summary of sustainability aspects in all scenarios

Table 8 summarizes some of the results from scenarios D0 through D5. Each column represents the difference between two scenarios mentioned and each row is one aspect of forest sustainability. The signs + and – denote the positive or negative change of that indicator between the two scenarios, while +/- means that the change is positive for some years and negative for others. For example, the first negative sign on Row 2 and Column 2 means that softwood pulpwood inventory is larger each year under Scenario D1, relative to Scenario D0.

Table 8 Changes in indicators of sustainability between different scenarios

	D1-D0 RFS+elec	D2-D1 tax	D3-D1 tech	D4-D1 AEO	D5-D1 25%
SW_Inventory	-	-/+	-	+	-
HW_Inventory	+	+	+	+	+
SW_Removal	+	+	+	-	+
HW_Removal	+	+	+	-	+
SW_Price	+	+	+	-	+
HW_Price	+	+	+	-/+	+
Displacement	+	-	+	+	+
Additional harvest	+	+	+	-	+
Logging residues	+	+/-	+	-	+
Timberland	+	-	+	-	+
<10 & >50 years	+	+/-	+	-	+
20~30 years	-	-	-	+	-

It can be observed that RFS mandates (D1) increase the removal and price levels of softwood and hardwood pulpwood, quantities of displacement from industry and additional harvesting, logging residues, timberland acres, and the share of the youngest and the oldest age classes, but reduces pine pulpwood inventory and the share of mid-aged trees in the forest. It suggests that the extra demand for pulpwood is satisfied by an increase in removal from newly expanded forestland and current forestland. However, since the removal is larger than that without bioenergy demand for pulpwood, the inventory becomes smaller, increasing the pulpwood price, which contributes to displacement from the existing forest industry. In addition, the new harvesting and management practices tend to reduce the share of mature trees in the future.

With additional increase in bioenergy demand for pulpwood due to the corn tax credit removal (D2), the removal and price levels of pulpwood continue to rise, and so does additional harvest. However, the displacement from the pulpwood industry, timberland acreage, and the share of mid-aged trees decline. This suggests that a slight increase in demand for pulpwood beyond D1 does not necessarily lead to greater loss in inventory all the time or more industry displacement. Considering the smaller forestland area, the additional demand beyond D1 might well be met by additional harvesting on existing forestland.

Moreover, as the demand for biofuel production grade wood increases further due to technologic improvement (D3), the price level of pulpwood, timberland acres, and additional harvest and displacement from industry increase, and the age class structure becomes more

bimodal. The largest bioenergy demand happens in scenario D5, which has the highest price and removal levels, quantity in displacement and additional harvesting, timberland acres, and logging residues. The two scenarios show that with a higher demand for pulpwood than in D1 or D2, more removal takes place and softwood inventory declines further while the price goes up. The extra demand for pulpwood as bioenergy feedstock is satisfied by additional replanting and harvesting from both existing and expanded forestland. The higher demand leads to a larger loss of softwood inventory as well as mature tree share in the forest, either of which has negative impacts on forest ecosystem services to industry and wildlife.

Scenario D4 follows a different biofuel production schedule, which results in lower price and removal levels for pine pulpwood, additional harvesting and timberland acres, while the age structure becomes less bimodal. All of these represent benefits for the forest ecological sustainability compared to D1, including increased biodiversity, wildlife habitat, and more sustainable forest industry. Also, the larger displacement from existing pulpwood industry does not produce higher pulpwood price at least for some years.

The maps of regional inventory change that are not shown in the main body of this paper are appended in the end. In the baseline scenario D0, all of the thirteen southern states except for KY have a smaller pine pulpwood inventory in 2037 compared to 2007. However, when pulpwood is used to meet bioenergy demand, as in Scenarios D1 to D4, all of the states are able to reduce the loss in pine pulpwood inventory. For example, six states, AL, AR, GA, TN, TX, and VA, which have smaller inventory in 2037 under D0, change into inventory increasing states. KY has an even larger inventory than before, and the rest of the states

considered here have a smaller reduction in inventory during the same time period. In Scenario D5, each state loses less pine pulpwood inventory than in D0, but more than in any other scenario. In particular, AR and VA turn into states with decreasing inventory, which is the opposite of Scenarios D1 to D4. On the other hand, hardwood pulpwood inventory is quite stable across all scenarios. Hardwood pulpwood does not change much for any of the thirteen states under all different scenarios presented here, which is probably due to the lower intensity of hardwood utilization in the South in most regions.

5.7 Comparison of POLYSYS and Integrated Modeling System

In order to compare the forest response in the integrated model with POLYSYS alone, this study uses the method in POLYSYS to get the stumpage price and pulpwood supply for each year. The pulpwood for bioenergy production comes from two sources: (1) additional harvest and thinning operations, and (2) displacement from the existing forest product industry. Both of them are approximated by starting with recent harvest and stumpage price and then applying pulpwood supply or demand elasticities to get the new stumpage price and/or new pulpwood supply or demand quantity. The supply and demand elasticities adopted are 0.34 and -0.42 respectively, based on elasticity estimates in literature (Newman, 1987; Carter, 1992; Newman and Wear, 1993; Prestemon and Wear, 2000; Polyakov et al., 2005; Lao and Zhang, 2008). Altogether, the percent change in pulpwood biomass supply in quantity can be roughly estimated to be (0.34+0.42) times percent change in stumpage price. Also, the removal in this approach is restricted to be no more than annual growth in order not

to reduce inventory, which is assumed to be constant over time. Thus, this consideration obtains the pulpwood stumpage price change based on the removals required for bioenergy production, based on the POLYSYS benchmark and simulation results for various scenarios. Also, the baseline pulpwood supply is matched to D0.

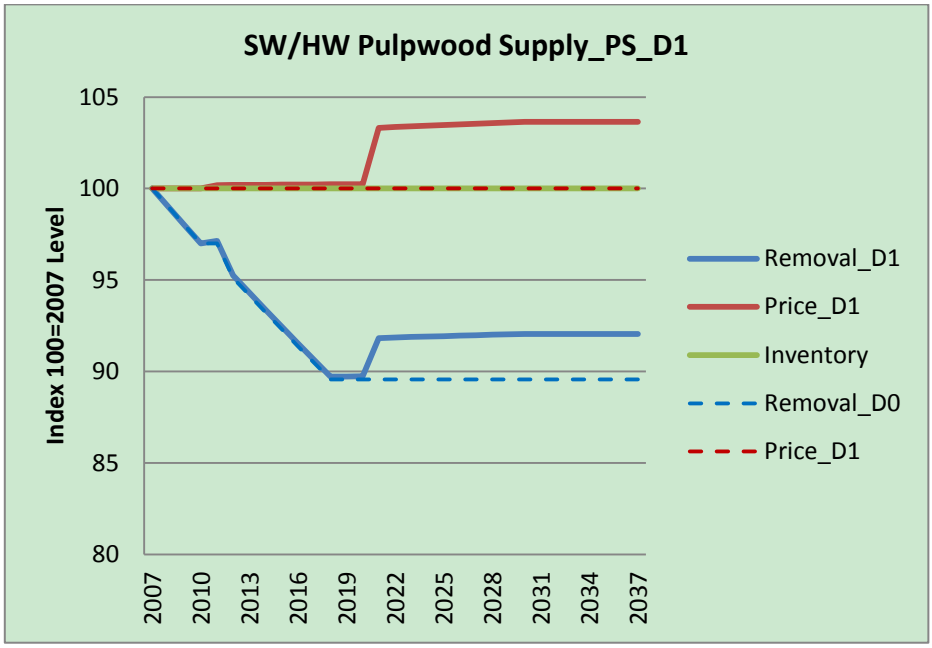
As illustrated in the following figures, after the year 2021, the pulpwood price and removal for scenario D1 are higher than those in D0, while inventory level stays the same as assumed. The price stays above the 2007 level all of the time and reaches about 3.6% higher than that of D0 in 2037. Although the removal level is still below 2007 level, it increases by 2% in the end. However, this result is not consistent with the earlier result shown in Figure 5.6 in Scenario D1, copied here as panel (b) in Figure 5.18. In the approach adopted by this study, the pulpwood price for both species does not come back to 2007 levels but has a rise compared with D0. The removals in POLYSYS without SRTS are at a lower level than that of this study, and so is the inventory, except for the dip in 2023 for pine pulpwood.

Due to the increase in bioenergy demand for forest product, removal goes up and inventory declines, contributing to a higher price than before. This higher price encourages additional harvesting and planting, which results in greater forestland acreage. However, the expanded forestland is not able to offset the increased removal. Thus, the inventory declines as a result of bioenergy demand. Compared with softwood, the change in hardwood pulpwood inventory is almost negligible.

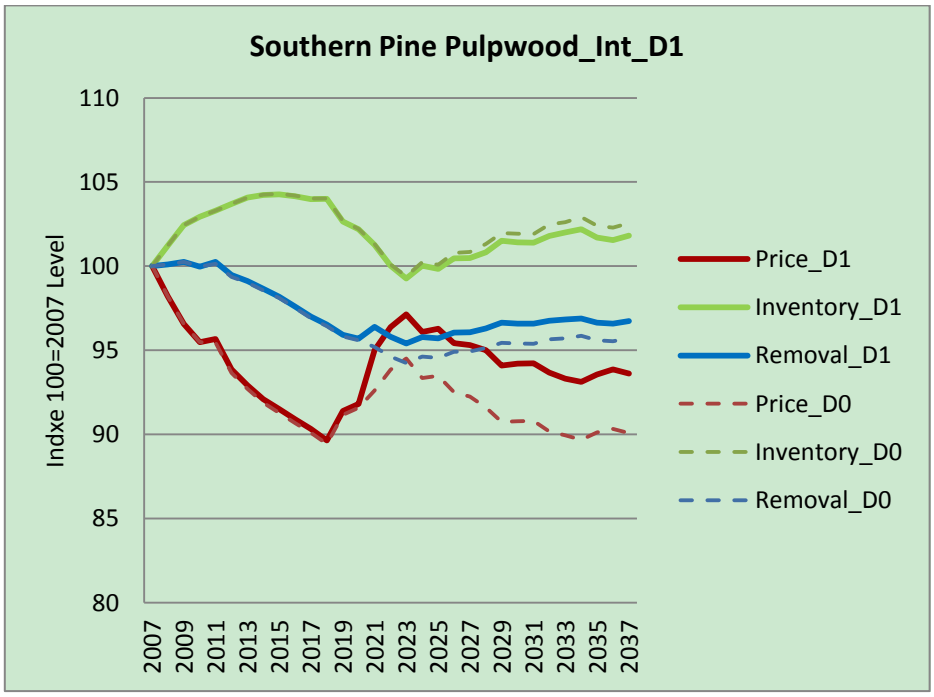
The constant forestland and inventory assumption implies that the increased removal to satisfy the new demand leads to a higher price but it does not cause forestland expansion or

inventory change. It means that the extra supply of forest products has to come from either intensified forest replanting/ harvesting or existing forest industry. However, there is no guarantee that bioenergy demand will be met while holding inventory constant each year. Plus, the possibility of forestland expansion is ignored, and so is the current trend in forest removal.

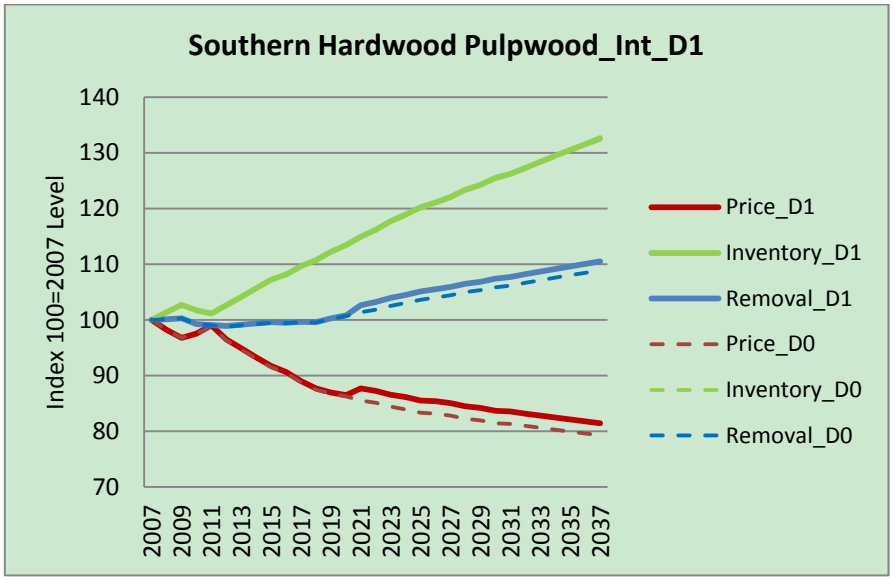
Figure 5.20 Comparison of POLYSYS and integrated modeling system under Scenario D1



(a) POLYSYS result of pulpwood supply under Scenario D1



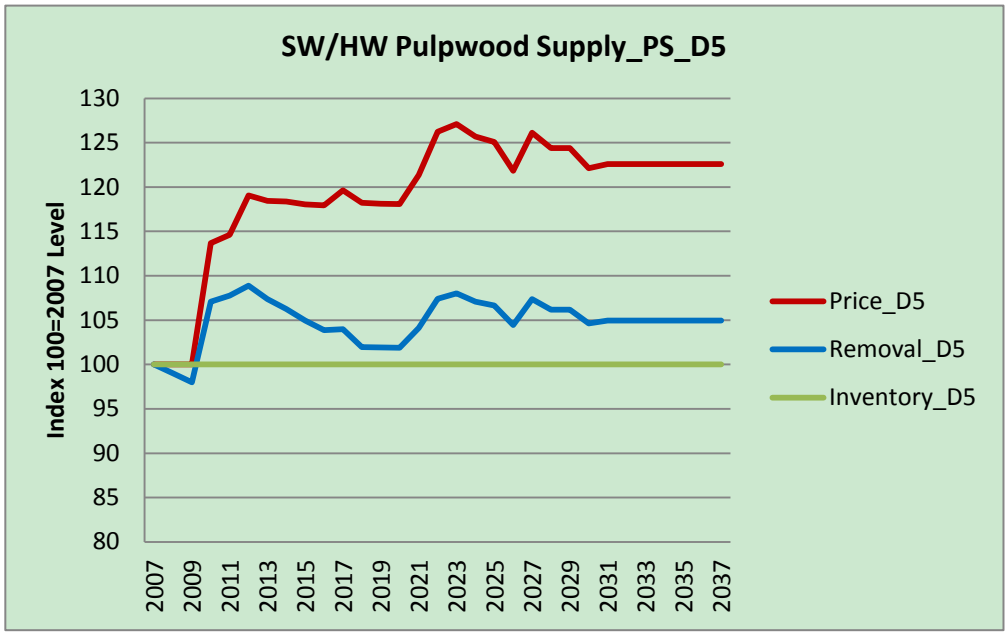
(b) Integrated model results of softwood pulpwood supply under D1



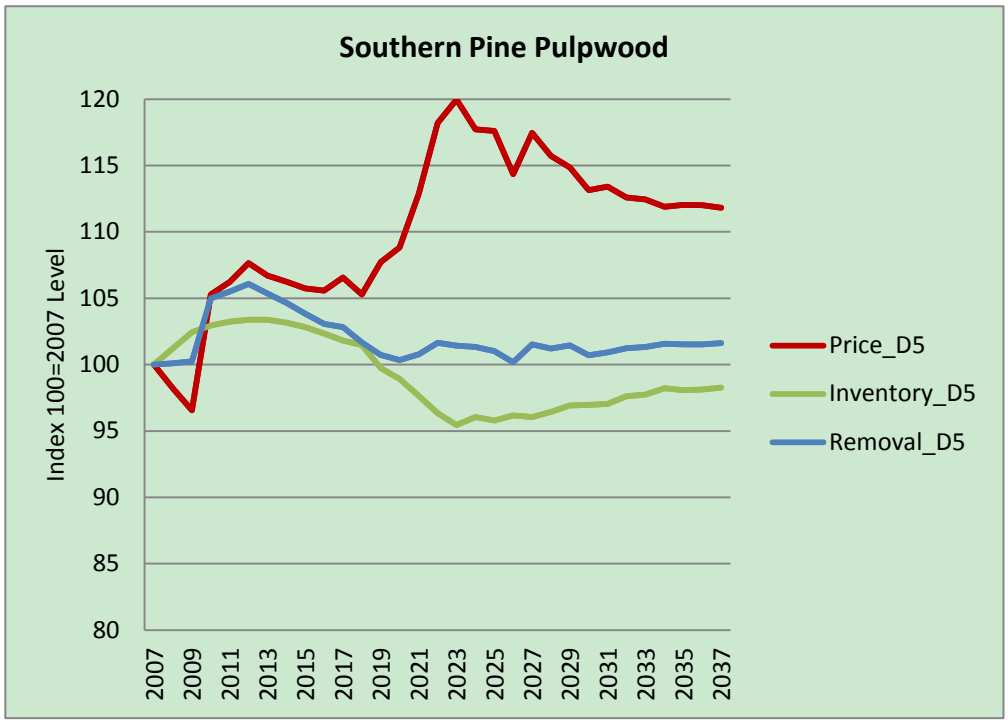
(c) Integrated model results of hardwood pulpwood supply under D1

The figures for scenarios D2 to D4 are shown in Appendix B, as they are very similar to scenario D1. Scenario D5 is a special case in that it dramatically changes the stumpage price and removal levels as illustrated in the figures below. Compared to the results in Figure 5.10 of Scenario D5 (also as Panel b) in Figure 5.19, POLYSYS without SRTS looks very close to the pine pulpwood result with the integrated model. This can be explained by the coincident similarity in the pulpwood inventory curve. Since POLYSYS adopts 0.34 and -0.42 for pulpwood supply and demand elasticities and SRTS assumes very similar elasticities, 0.5 and -0.5, the inventory curve of two model systems is similar and the removal and price levels can be consistent to some degree. On the other hand, the hardwood pulpwood has a very different inventory curve, which leads to the large divergence in the price and removal curves between two model systems.

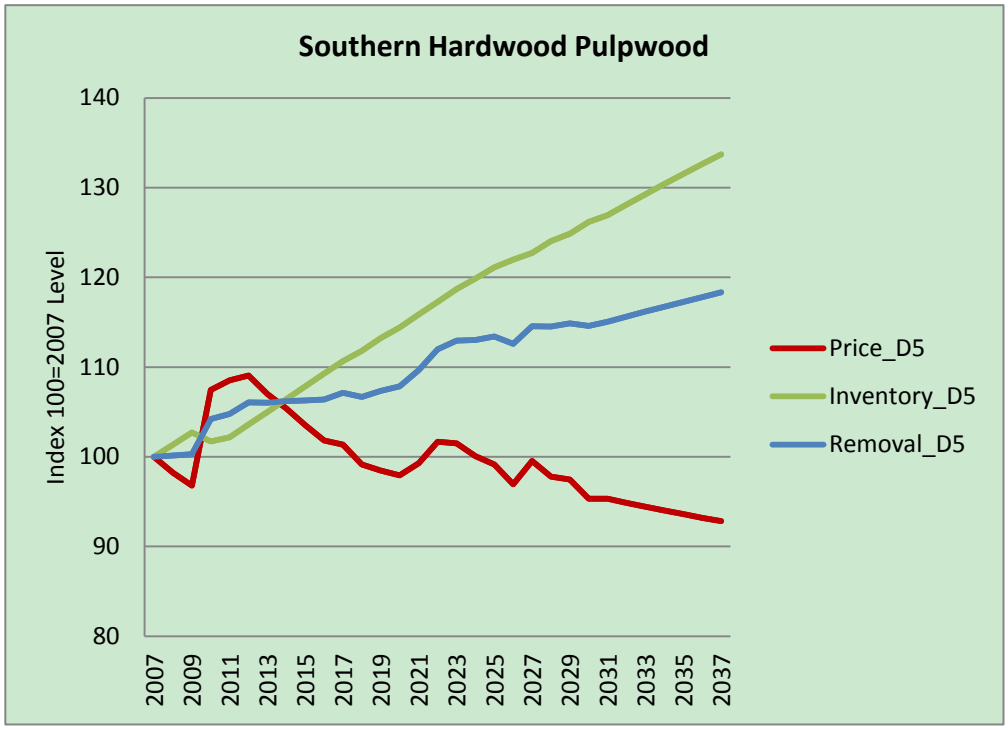
Figure 5.21 Comparison of POLYSYS and integrated modeling system under Scenario D5



(a) POLYSYS result of pulpwood supply under Scenario D5



(b) Integrated model results of softwood pulpwood supply under D5



(c) Integrated model results of hardwood pulpwood supply under D5

Also, previously mentioned state-level inventory change maps can illustrate the difference between POLYSYS and the integrated modeling system. Under constant inventory assumption in POLYSYS, softwood and hardwood pulpwood inventory in each state stays the same from 2007 to 2037, despite of changes in bioenergy demand. However, the integrated modeling system shows that some states end up with a larger softwood pulpwood inventory and others with a smaller inventory in 2037, while hardwood pulpwood inventory grows in all southeastern states. Moreover, the quantity and sign of pulpwood inventory change in each state vary with bioenergy demand.

In sum, the divergence between the integrated modeling system and POLYSYS alone is mainly caused by the constant inventory assumption, which ignores the dynamics of decision making on harvest and inventory. The integration of POLYSYS and SRTS models relaxes the static inventory assumption in POLYSYS and therefore is more realistic. Also, the integrated model enriches the forest resource information in terms of species, land management type, age structure, and spatial details. Without this integration, POLYSYS is not able to provide any dynamic information on forest resources.

6 CONCLUSIONS AND DISCUSSIONS

The integrated modeling system is able to improve the lack of dynamics and spatial details in existing model systems. With the integration methodology, it becomes possible to quantify some indicators (inventory, supply, management type, age structure, etc) of forest

sustainability at sub-regional level related with national bioenergy expansion, which was not solved before. Through this analysis, we understand that there are sustainability concerns related to bioenergy production after logging residues become depleted or too expensive, and the extent of the concerns depends on the bioenergy demand for woody biomass. Specifically, there are changes in forest product supply, inventory, and forest structure, concentrating in the states of North Carolina, South Carolina, Florida, Mississippi, Louisiana, and Oklahoma. Different regions/states have different forest outlooks in the future, which imply different sustainability concerns and thus possibly different counter measures to mitigating or addressing them. In addition, by postponing meeting bioenergy mandates to future years, some environmental benefits can be generated. These conclusions are further specified and discussed in following sections.

6.1 Conclusions

This study explores forest sustainability concerns related with biofuel production under uncertainties in policy, market, and technology. An increasing demand for forest biomass leads to changes in existing forest markets, removal, inventory, forest land use, age structure, and so on. Some of the impacts are positive, such as reducing timberland loss and bringing more income, whereas traditional industry displacement and the age structure gap are detrimental to the environment and ecology. Looking across all scenarios, some general conclusions can be drawn.

(1) Forest products

It is intuitive that a rise in biofuel production related demand for pulpwood would lead to a higher price and a larger removal of pine pulpwood and hardwood pulpwood, while the effect on inventory is not so straightforward. In all the scenarios studied here, pine pulpwood inventory falls below its 2007 level around 2023 but comes back by 2030, except for Scenario D5 where only 25% logging residues can be removed. While it is not hard to understand that softwood pulpwood inventory declines due to more bioenergy demand, the hardwood pulpwood product has a larger growth net removal for most of the time, meaning its net growth is abundant for both traditional forest products and bioenergy production studied here.

Therefore, softwood pulpwood inventory is more sensitive to changes in biofuel production. Softwood pulpwood's decreasing inventory contributes to a higher product price. As a result, increased harvest and industry displacement take place, at the magnitude of a million tons, given zero price elasticity. These effects are likely to hurt traditional industry by potentially forcing small pulp and paper mills out of business, but are beneficial for forest land owners who will see higher incomes than before. However, this situation might not sustain due to the instability in the market.

Nevertheless, the increased bioenergy demand for pulpwood has different impacts on the quantity of displacement and additional harvest, given zero price elasticity of bioenergy demand for pulpwood. The corn tax credit removal in Scenario D2 tends to encourage additional harvesting while it undermines displacement from the pulpwood industry, but the

new bioenergy demand and production schedule in Scenario D4 is the opposite. Meanwhile, both technological improvement and RFS mandates scenarios enhance both displacement and additional harvesting. Therefore, tax credit removal beyond meeting RFS mandates has a greater impact on forest land use change, while the delayed bioenergy demand and production schedule has a greater influence on the existing conventional pulpwood industry.

(2) Forest land management type

For all scenarios except for tax credit removal Scenario D2, as the bioenergy demand rises, there is less loss of forestland, but the total area of timberland is still declining. The scenario D2 has a higher bioenergy demand for pulpwood compared with that in RFS scenario D1, but its timberland acreage falls further as a result. The trend can be explained by the negligible change in pulpwood price and the relatively large increase in additional harvesting. These conditions might lead to further losses in forest land biodiversity and related wildlife habitat.

A higher pulpwood price incentivizes land owners to maintain forest land for pulpwood production, but sawtimber products are much more valuable, and they therefore play a major role in determining land-use change, as defined in the SRTS. Thus, the prosperous pulpwood market can not reverse the forest land declining trend. However, if ever the pulpwood price becomes comparable to sawtimber prices, pulpwood products then have more influence in land-use change decision making.

Generally, with a rise in biofuel production, the area of each of the five management types becomes larger but still downward sloping over time. On average, the area of pine

plantation and natural pine grows by 0.11% and 0.09% respectively after imposing RFS mandates in Scenario D1. From an ecological perspective, the reduction in timberland loss leads to positive impacts on forest ecosystem services, such as wildlife habitat, carbon sequestration, biodiversity, and nutrient preservation.

(3) Age class

The age class structure becomes more bimodal under biofuel production scenarios. Generally, there are more acres with trees under 15 yrs old and above 50 yrs old in the presence of a larger demand for pulpwood. Age classes from 16 to 49 altogether account for 42.7% of all ages in 2007 and fall to 36% in 2037 in RFS scenario D1, which is 37% in Scenario D0. This can result from more pulpwood harvesting, thus leaving less trees to grow older than 15 years. The mid-aged trees in the beginning of the time period age above 50 yrs old in the end of the 30-year period. However, Scenario D4, with a new delayed demand/production schedule is a special case in that it contradicts the RFS impacts to a small extent by increasing the share of mid-aged stands and reducing that of the youngest and the oldest stands.

Therefore, in the near future, the sawtimber industry is likely to be hurt as a result of a smaller share of mid-aged trees due to the increased pulpwood harvest in early years. Also, this loss of mid-aged trees in age class structure leads to losses in forest biodiversity, integrity, and wildlife habitat loss. The forest with the new age class structure as a result of anthropogenic activities is also likely to be more susceptible to pests and diseases.

(4) Uncertainties in policy, demand, and technology

Biofuel mandates, corn ethanol tax credit removal, and technology improvements in wood-based biofuels all promote a greater demand for woody biomass, but at different rates. The RFS mandates require a slightly larger amount of woody biomass than that of the AEO projection. Removing the $0.45 per gallon corn ethanol tax credit would lead to a 7.63% increase in demand for woody biomass, beyond RFS requirements, with an elasticity of substitution equaling 2. A 17.82% increase in woody biomass demand occurs with a 25% reduction in wood-based biofuel price, with the same elasticity of substitution. As expected, the more bio-demand for woody biomass, the more significant impacts there would be on the various aspects of forest sustainability. For instance, increasing forest biomass supply for ethanol from 0 to RFS requirement (D1), pulpwood price would rise by less than 1%, less than one million tons of pulpwood would be displaced from the existing industry, 0.1% more forest land would be maintained, and mid-age class (15-49) share would drop by 1 percentage point in 2037. However, if forest biomass supply is increased further (D5), by 20% by 2022, the pulpwood price rises by 20% for some years, and around 8 million tons of pulpwood would be displaced if pulpwood price elasticity of bioenergy demand is zero, with another 1% increase in forest land and another 1% decline in mid-age class share in 2037.

Nevertheless, the AEO scenario D4 makes a special case in that it demonstrates that by delaying meeting biofuel targets to future years, positive impacts on sustainability and forest markets can be generated. The results show that compared to the RFS scenario D1, there is less removal and less price increase in pine pulpwood, and more pulpwood from industry

displacement but less from additional harvest. Thus, the new production pattern has a greater impact on the existing forest market than on the land use change. Also, the age class structure is less bimodal compared to that of D1 the RFS scenario, which represents a shift to bring the structure back to its original status and thus positively impact sustainability.

Therefore, by postponing meeting the mandates, the forest price does not rise as much, the inventory increases, the quantity of additional harvest of timberland gets smaller, and the age class structure becomes less bimodal. The rationale can be that when there is more time to reach the same mandates, land owners and industry operators make adjustments according to market change. This actually mitigates the influence of bio-demand for woody biomass, including pulpwood.

(6) Uncertainty in logging residue utilization rate

The logging residue utilization rate needs to rise to approximately 50% in order to be sufficient for bioenergy production. If it is less than 25%, softwood pulpwood market price would go up by more than 20% for some years. Hardwood pulpwood inventory and removal is projected to rise over time, whereas softwood pulpwood inventory starts to decline as early as 2013. Also, given zero price elasticity, approximately 10 million tons of pulpwood is displaced from traditional industry for some of the years, which contributes to its much higher price in the future. The high price provides economic incentives for land owners to maintain timberland, including pine plantation and natural pine, but they are still unable to reverse the decline of pulpwood inventory. Meanwhile, forest age structure tends to be more bimodal and middle age trees are shifting out of the forest, which has a negative impact on

forest biodiversity, integrity, health, and timber industry. Thus, the influences on forest ecosystem services are mixed, with more logging residues and less timberland loss, yet much more serious forest biodiversity loss, future pulpwood inventory decline, and thus forest product market instability.

Moreover, as described in scenario D5 results, we know that harvesting more pulpwood does not produce proportionally more logging residues to meet bio-demand. The bio-demand for woody biomass has to be met to a large extent by pulpwood through additional harvesting and/or displacing the existing pulpwood market. There is little room for utilizing logging residues beyond RFS demand, if ever logging residues are sufficient for RFS mandates. However, expanded pulpwood harvest and displaced pulpwood industry tend to incur negative impacts on the current forest industry and some other forest ecosystem services.

6.2 Discussions

There have been other modeling efforts in exploring the aspects of forest resource sustainability responses to bioenergy production. One of them is the global dynamic forest model, with which Sedjo et al. (Sedjo & Sohngen, 2009) projected a 20% increase in global wood price. Also Abt (2010) predicted a significant pulpwood price increase and the insufficiency of logging residues in the Southeast to meet Renewable Portfolio Standards. NEMS (Brown et al., 2010; Brown & Baek, 2010) takes the supply data of agricultural

residues, energy crops, and forestry residues from the POLYSYS model. The supply of urban wood waste, mill residues, and forest residues are anticipated to be constant from 2020 to 2030. The GT-NEMS model predicts that biomass prices will increase significantly and concludes that with a national renewable electricity standard, agricultural and forest residues will "become a more valuable commodity" in the near future (Brown & Baek, 2010). In addition, since the current FASOM does not include competition for wood products in the existing industry, only mill residues and logging residues are considered as potential forest-based feedstocks. Among all of them, hardwood logging residues are found to be the major source. Under the Control Case, their price rises to $23.22/dry ton, and softwood logging residues prices reach $18.37/dry ton in 2022 (Beach & McCarl, 2010). This study tackles the problem of competition with existing industry and comes up with a range of pulpwood price changes. The softwood pulpwood price can rise by more than 20% if only 25% of logging residues are allowed to be removed. It should be noted that these studies are not entirely comparable due to their very different scopes and assumptions on forest resource competition with other sectors.

This study is calibrated to the result in POLYSYS to satisfy RFS and some electricity mandates, which requires usage of pulpwood. However, there is some research that casts doubt on this point. Ince et al. (Ince, Kramp et al. 2011) find that most wood energy consumption can be supplied by logging residues, but at the same time note that the national perspective "could mask some important local or sub-regional differences in wood markets." In this national-level study, logging residue recover rate is constrained to be not more than

60%. Nevertheless, the county-level removal rate adopted in POLYSYS is determined as a function of slope. Specifically, when slope is less than 40%, at least 30% of residue is left on site; when slope is greater than 40% but less than 80%, 60% of residue at max can be removed; no residues should be removed when slope is greater than 80% (B. Perlack et al., 2011). Results from this study show that some amount of pulpwood is used for bioenergy production to satisfy RFS and some electricity mandates and the average logging residues removed in the south is not more than 50% of available volume each year. It becomes either too expensive or not sustainable if more logging residues are removed. Then pulpwood, alternative to logging residues, enters the picture as bioenergy feedstock. In other words, pulpwood usage for bioenergy production begins even earlier than logging residue removal rate increases to 50% in the south. Therefore, the role of pulpwood for bioenergy production should be fully considered.

In evaluating forest sustainability concerns related with biofuel production under policy, market, and technology uncertainties, a dynamic resource model is needed with detailed information on the relationship between aspects of sustainability and biofuel production. This study takes the approach of linking two existing models, POLYSYS and SRTS. While consistency issues might exist, it solves the question with very limited data. Using the integrated method, one can establish a dynamic model that covers a multi-feedstock growing and harvest module, all types of biofuel production modules, and traditional industry modules, while providing links among them. As previously described,

FASOM solves the problem of competition between agriculture sectors and forest sectors but fails to provide forest resource information. Although a GTM integrated with dynamic CGE seems ideal, it is still lack of spatial details and requires extensive data input. Therefore, the methodology proposed in this study provides a relative quick way to draw some general conclusions for policy makers, and still retains spatial resolution at the regional level, with limited data about the emerging market.

This model enhances the strengths of both models and solves the static issue while generating more information. POLYSYS is strong in modeling agricultural crops and livestock and their use for bioenergy at the county level, but it does not have a dynamic forest sector or evaluate forest sustainability, although there has been some work in producing a more mature POLYSYS forestry model. Thus, POLYSYS is not yet able to examine the impacts of changes on policy, demand patterns, and technology on the forest sector. Meanwhile, SRTS projects forest product markets and also bioenergy implications on the forest sector, but it does not consider alternative sources for bioenergy, such as agricultural crops, switchgrass, SRWC, etc. It considers all other biomass resources as exogenous. Therefore, the MFM model connects the two to provide a more thorough and realistic solution to the relationship between forest sustainability and biofuel production. In addition to the advantage of dynamically and simultaneously examining competition between emerging markets and existing markets for multiple feedstocks, it further provides policy implications of biofuel mandates, tax credit removal, and technology improvements on forest resource sustainability. Through the comparison of forest results with the integration model

system and with POLYSYS alone, the results can differ to a large degree, especially for pine pulpwood, which is more sensitive to bioenergy demand. The integrated modeling system fixes the static issue of the forest sector in the POLYSYS model and is therefore more realistic.

Despite the advantages of this methodology, there are opportunities for improvement. The first one is the potential inconsistency associated with linking two PE models. While both POLYSYS and SRTS have forest components embedded in them but are not readily comparable, it is very hard to say if the forest-based biofuel production and demand for forest biomass are consistent in all three models. However, in order to avoid making inconsistent assumptions, this integrated modeling system takes results from POLYSYS as much as possible for SRTS input. The elasticity of substitution for the upper level in MFM is estimated from several POLYSYS demand driven runs and the linear production function for the second level is taken as given from POLYSYS results. In addition, the proportion of southeast states over national level is calculated from POLYSYS results by year, state, and price. It is notable that the supply and demand elasticities of forest product assumed in POLYSYS are 0.34 and -0.42, which are very close to those in SRTS, 0.5 and -0.5. Thus, the error from ignoring the difference in elasticities should not be great. Nevertheless, consistency is critical to the success of model integration. Further research on how to test the consistency would be desirable.

Secondly, one of the MFM's assumptions is that the biofuel related demand can be satisfied by domestic production. Trade of bioenergy internationally is not considered in the

scope of this study. The main reason is that SRTS applies to the southeastern regions and it is very difficult to track the trade between southeastern states and other states under national biofuel mandates. However, such considerations can be included in an extended version of MFM as described in Appendix A, given sufficient data. Besides all the equations used in the scenarios described here, an ethanol demand function is added to the system and modifications should be made to the supply and demand equilibrium.

Additionally, the benchmark in POLYSYS to which MFM calibrated and the baseline scenario D0 based on SRTS are not validated. Neither of them has been compared with other, similar projections, if there are any. However, the scenarios of tax credit removal, new demand pattern, and technological advancement are compared with the benchmark. The effects of the simulations are examined by how far they are from the benchmark. Nevertheless, since the RFS scenario D1 is compared with a baseline scenario D0, the assumption of scenario D0 might have some impact on the scenario D1. Therefore, validating the benchmark and scenario D0 has a greater impact on RFS scenario D1 than on simulation scenarios, which are more closely related to the MFM model structure and assumptions.

Lastly but not least, the supply and demand elasticities in the blended POLYSYS and SRST model are chosen from literature. However, elasticities evolve with the emerging bioenergy market. It would be more realistic to consider this change in both models, but no one is certain how much would that be; predicting the future elasticity would be difficult enough to constitute another dissertation. Thus, this study takes the forest product elasticities as given without adjusting to the evolving market.

REFERENCES

Abt, R. C., F. W. Cubbage, et al. (2000). "Southern forest resource assessment using the subregional timber supply (SRTS) model." *Forest Products Journal* 50(4): 25-33.

Ince, P. J., A. D. Kramp, et al. (2011). "Modeling future US forest sector market and trade impacts of expansion in wood energy consumption." *Journal of Forest Economics 17(2):142-156.*

Abt, R. C., Cubbage, F. W., & Abt, K. L. (2007). Projecting southern timber supply for multiple products by subregion. *Forest Products Journal, 59,* 718.

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, Aug 2010*.

Adamowicz, W., & Adamowicz, W. (2003). Economic indicators of sustainable forest management: Theory versus practice. *Journal of Forest Economics*, *9*(1), 27-40.

Air Improvement Resource, I. (2009). *Review of CARB's low carbon fuel standard proposal*Renewable Fuels Association 2009.

Statement at the hearing on indirect land use and renewable biomass provisions of the renewable fuels standard: Subcommittee on Conservation, Credit, Energy, and Research of the U.S. House Committee on Agriculture, Washington, D.C., Statement at the

hearing on indirect land use and renewable biomass provisions of the renewable fuels standard: (2009).

Baker, M. L., Hayes, D. J., & Babcock, B. A. (2008). Crop-based biofuel production under acreage constraints and uncertainty. *Center for Agricultural and Rural Development (CARD) Publications 2008.*

Banse, M., Tabeau, A., Woltjer, G., & van Meijl, H. (2007). Impact of EU biofuel policies on world agricultural and food markets. *Paper Submitted for the GTAP Conference, Purdue University, Indian 2007.*

Beach, R. H., Daigneault, A. J., McCarl, B. A., & Rose, S. K. (2010). Modeling alternative policies for ghg mitigation from forestry and agriculture. *Proceedings Issues, 2010: Climate Change in World Agriculture: Mitigation, Adaptation, Trade and Food Security, June 2010, Stuttgart-Hohenheim, Germany.*

Beach, R. H., & McCarl, B. A. (2010). US agricultural and forestry impacts of the energy independence and security act: FASOM results and model description 2010.

Berndt, E. R. (1976). Reconciling alternative estimates of the elasticity of substitution. *The Review of Economics and Statistics, 58*(1), 59-68.

Biomass Research and Development Initiative (BRDI). (2009). *Increasing feedstock production for biofuels: Economic drivers, environmental implications, and the role of research* Biomass Research and Development Board, Washington, D.C 2009.

Brown, M. A., & Baek, Y. (2010). The forest products industry at an energy/climate crossroads. *Energy Policy, 38(12) 7665-7675.*

Brown, M. A., Gumerman, E., Baek, Y., Wang, J., Morris, C., & Wang, Y. (2010). Renewable energy in the south. Southeast Energy Efficiency Alliance, Atlanta, GA Dec 2010.

Carter, D. R. (1992). Effects of supply and demand determinants on pulpwood stumpage quantity and price in texas. *Forest Science, 38*(3), 652-660.

Darlington, T. L. (2009). Land use effects of US corn-based ethanol. *Air Improvement Resource, Inc., Novi, MI.Http://www.Scribd.com/doc/13474497/Land-use-Effects-of-US-Cornbased-Ethanol,*

de Fraiture, C., Giordano, M., & Liao, Y. (2008). Biofuels and implications for agricultural water use: Blue impacts of green energy. *Water Policy, 10*(1), 67-81.

Dicks, M. R., Campiche, J., Ugarte, D. D. L. T., Hellwinckel, C., Bryant, H. L., & Richardson, J. W. (2009). Land use implications of expanding biofuel demand. *Journal of Agricultural and Applied Economics, 41*(02)

Didion, M., Fortin, M. J., & Fall, A. (2007). Forest age structure as indicator of boreal forest sustainability under alternative management and fire regimes: A landscape level sensitivity analysis. *Ecological Modelling, 200*(1-2), 45-58.

Diewert, W. E. (1973). Applications of duality theory *University of British Columbia and Research Projects Group, Strategic Planning and Research Division, Dept. of Manpower and Immigration*.

Du, X., & Hayes, D. J. (2008). Impact of ethanol production on US and regional gasoline prices and on the profitability of the US oil refinery industry, the. *Staff General Research Papers,*

Elobeid, A., & Tokgoz, S. (2006). Removal of US ethanol domestic and trade distortions: Impact on US and brazilian ethanol markets. Center for Agricultural and Rural Development, Iowa State University, Ames, Iowa. October 2006.

Elobeid, A., & Tokgöz, S. (2006). *Removal of US ethanol domestic and trade distortions: Impact on US and brazilian ethanol markets* Center for Agricultural and Rural Development, Iowa State University.

Energy Information Administration. http://www.eia.doe.gov/cneaf/electricity/esr/table5.html

Energy Information Administration (EIA). (2009). The national energy modeling system: An overview 2009.

Renewable Fuel Standards. the US Energy Independence and Security Act of 2005, (2005).

Renewable Fuel Standards. the US Energy Independence and Security Act of 2007 (2007).

Regulation of Fuels and Fuel Additives: Changes to Renewable Fuel Standard Program; Final Rule, (2010). Retrieved from http://www.epa.gov/otaq/fuels/renewablefuels/regulations.htm

Fargione, J., Hill, J., Tilman, D., Polasky, S., & Hawthorne, P. (2008). Land clearing and the biofuel carbon debt. *Science, 319*(5867), 1235.

Forest Inventory and Analysis National Program. http://199.128.173.26/fido/index.html

Fritsche, U. R., Sims, R. E. H., & Monti, A. (2010). Direct and indirect land-use competition issues for energy crops and their sustainable production–an overview. *Biofuels, Bioproducts and Biorefining, 4*(6), 692-704.

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

Haq, Z. (2002). *Biomass for electricity generation* Energy Information Administration, United States, 2002.

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

Hardie, I. W., & Parks, P. J. (1997). Land use with heterogeneous land quality: An application of an area base model. *American Journal of Agricultural Economics, 79*(2), 299-310.

Harvey, B. D., Leduc, A., Gauthier, S., & Bergeron, Y. (2002). Stand-landscape integration in natural disturbance-based management of the southern boreal forest. *Forest Ecology and Management, 155*(1-3), 369-385.

Hayes, D., Babcock, B., Fabiosa, J., Tokgoz, S., Elobeid, A., Yu, T. H., et al. (2009). Biofuels: Potential production capacity, effects on grain and livestock sectors, and implications for food prices and consumers. *Journal of Agricultural and Applied Economics, 41*(02)

Hertel, T., Tyner, W., & Birur, D. (2010). The global impacts of biofuel mandates. *The Energy Journal, 31*(1), 75-100.

Huang, M. Y., & Alavalapati, J. R. R. (2009). Economy-wide impacts of forest bioenergy in florida: A computable general equilibrium analysis.

Ianchovichina, E., & McDougall, R. (2001). Structure of dynamic GTAP. GTAP technical paper 17. *Center for Global Trade Analysis, Available on Line at Www.Gtap.Org,*

Ince, P. J., A. D. Kramp, et al. (2011). Modeling future US forest sector market and trade impacts of expansion in wood energy consumption. *Journal of Forest Economics.*

Liao, X., & Zhang, Y. (2008). An econometric analysis of softwood production in the US south: A comparison of industrial and nonindustrial forest ownerships. *Forest Products Journal, 58*(11), 69-74.

Mann, M., & Spath, P. (2001). A life cycle assessment of biomass cofiring in a coal-fired power plant. *Clean Technologies and Environmental Policy, 3*(2), 81-91.

Mapemba, L. D., Epplin, F. M., & Huhnke, R. L. Environmental consequences of ethanol from corn grain, ethanol from lignocellulosic biomass, and conventional gasoline.

Mathews, J. A., & Tan, H. (2009). Biofuels and indirect land use change effects: The debate continues. *Biofuels, Bioproducts and Biorefining, 3*(3)

McCormick, B., & Golden, C. (2005). Effects of biodiesel on pollutant emissions. *National Renewable Energy Laboratory,*

Mooney, H. A., & Hobbs, R. J. (2000). *Invasive species in a changing world* Island Pr.

National Research Council of the National Academies. (2007, 2008). *Water implications of biofuels production in the U.S.*

Newman, D. H. (1987). An econometric analysis of the southern softwood stumpage market: 1950-1980. *Forest Science, 33*(4), 932-945.

Newman, D. H., & Wear, D. N. (1993). Production economics of private forestry: A comparison of industrial and nonindustrial forest owners. *American Journal of Agricultural Economics, 75*(3), 674-684.

Oates, W. E., Portney, P. R., & McGartland, A. M. (1989). The net benefits of incentive-based regulation: A case study of environmental standard setting. *American Economic Review, 79*(5), 1233-1242.

Palatnik, R. R., & Roson, R. (2009). Climate change assessment and agriculture in general equilibrium models: Alternative modeling strategies. *Fondazione Eni Enrico Mattei Working Papers, ,* 328.

Perlack, B., Stokes, B., Brandt, C., Turhollow, A. F., Wright, L., Eaton, L., et al. (2011). *Biomass feedstock resource availability: Update to the billion-ton resource assessment*A study sponsored by Office of Biomass Program U.S. Department of Energy. Prepared by Oak Ridge National Laboratory.

Perlack, R. D., Wright, L. L., Turhollow, A. F., Graham, R. L., Stokes, B. J., & Erbach, D. C. (2005). Biomass as feedstock for A bioenergy and bioproducts industry: The technical feasibility of a billion-ton annual supply.

Peskett, L., Slater, R., Stevens, C., & Dufey, A. (2007). Biofuels, agriculture and poverty reduction. *Paper Produced for the DFID Renewable NaturalResourcesand Agriculture Team, ODI, London,*

Polyakov, M., Teeter, L. D., & Jackson, J. D. (2005). REVIEWED ARTICLES-econometric analysis of alabama's pulpwood market. *Forest Products Journal and Index, 55*(1), 41-44.

Prestemon, J. P., & Wear, D. N. (2000). Linking harvest choices to timber supply. *Forest Science, 46*(3), 377-389.

Ronneberger, K., Berrittella, M., Bosello, F., & Tol, R. S. J. (2009). KLUM@ GTAP: Introducing biophysical aspects of land-use decisions into a computable general equilibrium model a coupling experiment. *Environmental Modeling and Assessment, 14*(2), 149-168.

Rosegrant, M. W. (2008). *Biofuels and grain prices: Impacts and policy responses* International Food Policy Research Institute Washington, DC.

Sandén, B. A., & Azar, C. (2005). Near-term technology policies for long-term climate targets—economy wide versus technology specific approaches. *Energy Policy, 33*(12), 1557-1576.

Saundry, P. (2009). Calculation of lifecycle greenhouse gas emissions for the renewable fuel standard.

Schmidhuber, J., & Tubiello, F. N. (2007). Global food security under climate change. *Proceedings of the National Academy of Sciences of the United States of America, 104*(50), 19703-19708.

Searchinger, T., Heimlich, R., Houghton, R., Dong, F., Elobeid, A., Fabiosa, J., et al. (2008). Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science, 319*(5867), 1238.

Sedjo, R. A., & Sohngen, B. (2009). The implication of increased use of wood for biofuel production. *Washington, DC: Resources for the Future.,* (Issues brief 09-04)

Sheehan, J. J. (2009). Sustainable biofuels: A commonsense perspective on California's approach to biofuels & global land use. *Industrial Biotechnology, 5*(2), 93-103.

Smith, W. B. (2009). Forest resources of the united states, 2007. *Gen,*

Sohngen, B., Golub, A., & Hertel, T. W. (2009). 11 the role of forestry in carbon sequestration in general equilibrium models. *Economic Analysis of Land use in Global Climate Change Policy,* , 279.

Sohngen, B., Mendelsohn, R., & Sedjo, R. (2001). A global model of climate change impacts on timber markets. *Journal of Agricultural and Resource Economics, 26*(2), 326-343.

Sohngen, B., Tennity, C., Hnytka, M., & Meeusen, K. (2009). Global forestry data for the economic modeling of land use. *Economic Analysis of Land use in Global Climate Change Policy*, , 49?1.

Tokgoz, S., Elobeid, A., Fabiosa, J., Hayes, D. J., Babcock, B. A., Yu, T. H. E., et al. (2007). Long-term and global tradeoffs between bio-energy, feed, and food. Paper presented at the *Selected Paper Prepared for Presentation at the American Agricultural Economics Association Annual Meeting, Portland, OR, July29August1*,

Treguer, D., & Sourie, J. (2006). The impact of biofuel production on farm jobs and income: The french case. *Article Presented at the 96th EAAE Seminar in Tanikon, Switzerland, January*,

Tyner, W. E. (2007). US ethanol Policy—Possibilities for the future. *West Lafayette (IN): Purdue University.Purdue Extension Publication ID-342-W.(25 June 2008*,

USDA. (2010). USDA agricultural projections to 2019.

Van der Werf, E., & Peterson, S. (2009). Modeling linkages between climate policy and land use: An overview. *Agricultural Economics, 40*(5), 507-517.

Von Braun, J., Ahmed, A., Asenso-Okyere, K., Fan, S., Gulati, A., Hoddinott, J., et al. (2008). High food prices: The what, who, and how of proposed policy actions. *Policy Briefs*,

Wear, D. N., Carter, D. R., & Prestemon, J. (2007). The US South's timber sector in 2005: A prospective analysis of recent change. *Asheville (NC): USDA Forest Service Southern Research Station,*

Wear, D., Abt, R., Alavalapati, J., Comatas, G., Countess, M., & McDow, W. (2010). The south's outlook for sustainable forest bioenergy and biofuels production.*USDA Forest Service, Southern Research Station 2010.*

APPENDICES

Appendix A

A.1 Tables of logging residues and pulpwood from the South

Table A.1 1 pulpwood supply for bioenergy from the southeast by year and price in POLYSYS (without federal land)

	50	*60*	*70*	*80*	*90*	*100*	*110*	*120*	*130*	*140*	*150*	*160*	*170*	*180*	*190*	*200*
2009	0.1	1.2	6.4	15.2	24.2	31.7	38.6	44.9	51.1	57.5	63.2	69.0	74.7	79.8	84.0	89.7
2010	0.1	1.2	6.5	15.4	24.5	32.1	39.1	45.5	51.8	58.2	64.1	69.9	75.7	80.8	85.1	90.9
2011	0.1	1.2	6.6	15.6	24.8	32.5	39.7	46.1	52.4	59.0	64.9	70.9	76.7	81.9	86.3	92.1
2012	0.1	1.2	6.7	15.8	25.2	33.0	40.2	46.7	53.1	59.8	65.8	71.8	77.7	83.0	87.4	93.3
2013	0.1	1.3	6.8	16.1	25.7	33.6	41.0	47.6	54.2	61.0	67.1	73.2	79.3	84.7	89.2	95.2
2014	0.1	1.3	6.9	16.4	26.2	34.3	41.8	48.5	55.2	62.2	68.4	74.7	80.8	86.3	90.9	97.0
2015	0.1	1.3	7.1	16.7	26.7	34.9	42.6	49.5	56.3	63.4	69.7	76.1	82.3	88.0	92.6	98.9
2016	0.1	1.3	7.2	17.0	27.2	35.6	43.4	50.4	57.4	64.5	71.0	77.5	83.9	89.6	94.4	100.7
2017	0.1	1.4	7.3	17.4	27.7	36.2	44.2	51.3	58.4	65.7	72.3	78.9	85.4	91.2	96.1	102.6
2018	0.1	1.4	7.4	17.6	28.1	36.8	44.9	52.1	59.3	66.8	73.4	80.2	86.7	92.7	97.6	104.2
2019	0.1	1.4	7.6	17.9	28.5	37.4	45.5	52.9	60.2	67.8	74.6	81.4	88.1	94.1	99.1	105.8
2020	0.1	1.4	7.7	18.2	28.9	37.9	46.2	53.7	61.1	68.8	75.7	82.6	89.4	95.5	100.6	107.4
2021	0.1	1.5	7.8	18.4	29.4	38.5	46.9	54.5	62.0	69.8	76.8	83.8	90.7	96.9	102.1	109.0
2022	0.1	1.5	7.9	18.7	29.8	39.1	47.6	55.3	62.9	70.8	77.9	85.1	92.1	98.3	103.6	110.6
2023	0.1	1.5	8.0	18.9	30.1	39.5	48.1	55.9	63.6	71.6	78.8	86.0	93.0	99.4	104.7	111.7
2024	0.1	1.5	8.1	19.1	30.4	39.9	48.6	56.5	64.3	72.4	79.6	86.9	94.0	100.4	105.8	112.9
2025	0.1	1.5	8.2	19.3	30.8	40.3	49.1	57.1	65.0	73.1	80.4	87.8	95.0	101.5	106.9	114.1
2026	0.1	1.5	8.2	19.5	31.1	40.7	49.6	57.7	65.6	73.9	81.3	88.7	96.0	102.5	108.0	115.3
2027	0.1	1.6	8.3	19.7	31.4	41.1	50.1	58.2	66.3	74.6	82.1	89.6	97.0	103.6	109.1	116.4
2028	0.1	1.6	8.4	19.9	31.7	41.6	50.6	58.8	67.0	75.4	82.9	90.5	97.9	104.6	110.2	117.6
2029	0.1	1.6	8.5	20.1	32.0	42.0	51.1	59.4	67.6	76.1	83.8	91.4	98.9	105.7	111.3	118.8
2030	0.1	1.6	8.6	20.3	32.3	42.4	51.7	60.0	68.3	76.9	84.6	92.3	99.9	106.7	112.4	120.0

Table A.1 2 logging residues supply of the southern states by year and price from POLYSYS (without federal land)

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20	5.84	5.86	5.87	5.89	5.91	5.93	5.95	5.96	5.98	6.00	6.01
30	16.15	16.20	16.26	16.31	16.38	16.46	16.53	16.61	16.68	16.74	16.79
40	17.31	17.36	17.41	17.46	17.53	17.61	17.68	17.76	17.83	17.88	17.94
50	17.92	17.97	18.02	18.08	18.15	18.22	18.30	18.37	18.45	18.50	18.56
60	18.33	18.39	18.44	18.49	18.56	18.64	18.71	18.79	18.86	18.91	18.97
70	18.64	18.69	18.74	18.79	18.87	18.94	19.02	19.09	19.17	19.22	19.27
80	18.89	18.94	18.99	19.04	19.11	19.19	19.27	19.34	19.41	19.47	19.52
90	19.09	19.14	19.19	19.24	19.32	19.39	19.47	19.54	19.62	19.67	19.72
100	19.28	19.33	19.38	19.43	19.50	19.58	19.65	19.73	19.80	19.85	19.91
110	19.45	19.50	19.55	19.60	19.67	19.75	19.83	19.90	19.97	20.03	20.08
120	19.62	19.67	19.72	19.77	19.84	19.92	19.99	20.07	20.14	20.19	20.25
130	19.75	19.80	19.86	19.91	19.98	20.06	20.13	20.21	20.28	20.33	20.39
140	19.87	19.92	19.97	20.02	20.10	20.17	20.25	20.32	20.39	20.45	20.50
150	19.98	20.03	20.08	20.13	20.21	20.28	20.36	20.43	20.51	20.56	20.61
160	20.08	20.13	20.18	20.23	20.31	20.38	20.46	20.53	20.61	20.66	20.71
170	20.17	20.22	20.27	20.33	20.40	20.48	20.55	20.62	20.70	20.75	20.81
180	20.26	20.31	20.36	20.41	20.49	20.56	20.64	20.71	20.78	20.84	20.89
190	20.33	20.38	20.43	20.48	20.56	20.63	20.71	20.78	20.85	20.91	20.96
200	20.49	20.54	20.59	20.64	20.72	20.79	20.87	20.94	21.02	21.07	21.12

Table A.1.2 Continued

	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20	6.02	6.04	6.05	6.05	6.06	6.06	6.07	6.07	6.07	6.08	6.08
30	16.84	16.90	16.95	16.97	16.99	17.01	17.03	17.06	17.08	17.10	17.12
40	17.99	18.04	18.10	18.12	18.14	18.16	18.18	18.20	18.22	18.25	18.27
50	18.61	18.66	18.71	18.74	18.76	18.78	18.80	18.82	18.84	18.86	18.88
60	19.02	19.07	19.13	19.15	19.17	19.19	19.21	19.23	19.26	19.28	19.30
70	19.33	19.38	19.43	19.45	19.48	19.50	19.52	19.54	19.56	19.58	19.60
80	19.57	19.63	19.68	19.70	19.72	19.74	19.77	19.79	19.81	19.83	19.85
90	19.78	19.83	19.88	19.90	19.93	19.95	19.97	19.99	20.01	20.03	20.05
100	19.96	20.02	20.07	20.09	20.11	20.13	20.15	20.17	20.20	20.22	20.24
110	20.13	20.19	20.24	20.26	20.28	20.30	20.33	20.35	20.37	20.39	20.41
120	20.30	20.35	20.41	20.43	20.45	20.47	20.49	20.51	20.53	20.56	20.58
130	20.44	20.49	20.55	20.57	20.59	20.61	20.63	20.65	20.67	20.70	20.72
140	20.55	20.61	20.66	20.68	20.70	20.72	20.74	20.77	20.79	20.81	20.83
150	20.67	20.72	20.77	20.79	20.81	20.84	20.86	20.88	20.90	20.92	20.94
160	20.77	20.82	20.87	20.89	20.91	20.93	20.96	20.98	21.00	21.02	21.04
170	20.86	20.91	20.96	20.98	21.01	21.03	21.05	21.07	21.09	21.11	21.14
180	20.94	21.00	21.05	21.07	21.09	21.11	21.13	21.15	21.18	21.20	21.22
190	21.01	21.07	21.12	21.14	21.16	21.18	21.21	21.23	21.25	21.27	21.29
200	21.17	21.23	21.28	21.30	21.32	21.34	21.37	21.39	21.41	21.43	21.45

A.2 Tables of MFM results

Table A.2 1 MFM results of scenarios D2, D3 and D4

Year 2022		T(corn)=23.8	T(wood)=-0.25	Demand =AEO (2022)
Total ethanol quantity		0	0	-26.90
Ethanol Price		11.072	-5.201	0
Corn	feedstock price	0	0	0
	feedstock input	-7.313	-3.67	-26.90
	ethanol price	23.8	0	0
	ethanol quantity	-7.313	-3.67	-26.90
Stover	feedstock price	0	0	0
	feedstock input	7.627	-3.67	-26.90
	ethanol price	0	0	0
	ethanol quantity	7.627	-3.67	-26.90
	feedstock price	0	0	0
	feedstock input	7.627	-3.67	-26.90
	ethanol price	0	0	0
Switchgrass	ethanol quantity	7.627	-3.67	-26.90
	feedstock price	0	0	0
	feedstock input	7.627	-3.67	-26.90
	ethanol price	0	0	0
Poplar	Ethanol quantity	7.627	-3.67	-26.90
	feedstock price	0	0	0
	feedstock input	7.627	17.82	-26.90
	ethanol price	0	-25	0
Wood	ethanol quantity	7.627	17.82	-26.90
	feedstock price	0	0	0
	feedstock input	7.627	-3.67	-26.90
	ethanol price	0	0	0
Other	ethanol quantity	7.627	-3.67	-26.90

Table A.2 2 MFM results of Feedstock Demand Change under AEO Projection when Theta Equals 0.7 (Unit: %)

	Corn	Stover	Switchgrass	poplar	Wood	other
2009	15.586				15.586	15.586
2010	14.713				14.713	
2011	17.923	17.923	17.923		17.923	17.923
2012	17.528	17.528	17.528		17.528	17.528
2013	12.529	12.529	12.529		12.529	12.529
2014	7.839	7.839	7.839		7.839	7.839
2015	-0.98	-0.98	-0.98		-0.98	-0.98
2016	-4.436	-4.436	-4.436		-4.436	-4.436
2017	-7.79	-7.79	-7.79		-7.79	-7.79
2018	-11.615	-11.615	-11.615	-11.615	-11.615	-11.615
2019	-15.666	-15.666	-15.666	-15.666	-15.666	-15.666
2020	-18.362	-18.362	-18.362	-18.362	-18.362	-18.362
2021	-22.874	-22.874	-22.874	-22.874	-22.874	-22.874
2022	-26.899	-26.899	-26.899	-26.899	-26.899	-26.899
2023	-23.186	-23.186	-23.186	-23.186	-23.186	-23.186
2024	-19.504	-19.504	-19.504	-19.504	-19.504	-19.504
2025	-15.498	-15.498	-15.498	-15.498	-15.498	-15.498
2026	-11.771	-11.771	-11.771	-11.771	-11.771	-11.771
2027	-8.116	-8.116	-8.116	-8.116	-8.116	-8.116
2028	-4.41	-4.41	-4.41	-4.41	-4.41	-4.41
2029	-0.714	-0.714	-0.714	-0.714	-0.714	-0.714
2030	3.272	3.272	3.272	3.272	3.272	3.272

A.3 Unit Conversion

One ton of corn grain = 35.7 bushels
1 green ton= 2 dry tons
1 MCF = 35.5 green tons for softwood
1 MCF = 37 green tons for hardwood

A.4 Extended MFM

Demand for ethanol in the US would be specified as a function of its price, gasoline price, as well as macroeconomic variables such as GDP and population. Currently, U.S. gasoline is required to include up to 10% ethanol by volume. Generally, the gasoline mixed with 10% ethanol can be used by conventional vehicles. The feasibility of a 15-20% blend is currently under study, so it is not included for now. Blended with gasoline to 10%, biofuel is more of a complement to gasoline. However, in the case of biofuel mix E85, which is getting increasingly common in the US, biofuel becomes more of a substitute to gasoline. Most E-85 capable vehicles are flex-fuel vehicles. Thus, the composition of the vehicle fleet should be included in the function. Given the influence of ethanol incentives in promoting its use we also include two additional variables: 1) Federal ethanol credits, and, 2) Renewable Fuel Standards (particularly RFS1 & RFS2). The demand function can be stated as:

$$Q_D = g(P - \text{Credit}, Pg, GDP, E85, POP, RFS)$$

$$E85_t = E85_{t-1} * (1 + m_t)$$

where

Q_D is the Marshallian demand for ethanol in the US market. P is the ethanol price and Pg gasoline price. E85 denote the share of E85 vehicle fleet, while m_t is the exogenous growth rate. t is the time period. POP, RFS and Credit stand for population, renewable fuel standards, and ethanol credit, respectively.

The supply and demand equilibrium should also be modified to:

$Q_D = Q_S + \text{Net Import} + \text{Stock change}$

where net imports is specified exogenously.

Therefore, the derived demand x_i for feedstock i can be expressed as

$$x_i = \frac{\partial C}{\partial Pi} = (Q_D - \text{Net Import} - \Delta\text{stock}) * \sum_j \frac{\partial UC}{\partial cij} . \frac{\partial cij}{\partial Pi}$$

So the new econometric function for ethanol demand becomes

$$\ln Q_{Dt} = \alpha_0 + \alpha_1 \ln(P - \text{Credit})_t + \alpha_2 \ln Pg_t + \alpha_3 \ln E85_t + \alpha_4 \ln GDP_t + \alpha_5 \ln POP_t$$

$$+ \alpha_6 \ln RFS_t + \alpha_7 t + \alpha_8 \ln Q_{Dt-1} + \varepsilon_t$$

$$\alpha_4 \ln RGDPPC_t$$

$$E85_t = E85_{t-1} * (1 + m_t)$$

Then the derived demand for feedstock i can be written as:

$$x_i = \frac{\partial C}{\partial Pi} = Qs * \sum_j \frac{\partial UC}{\partial cij} . \frac{\partial cij}{\partial Pi} = (Q_D - \text{Net Import} - \Delta\text{stock}) * \sum_j b_{0ij} . b_{iji} . \frac{UC * a_i c_i^{(\frac{1}{\sigma} - 2)}}{\sum_i a_i c_i^{(1-\sigma)/\sigma}}$$

Thus the new demand function is added to the system and the supply equation is also modified accordingly:

Supply: $y = Q - \text{import} - \Delta\text{stock}$

Demand: $P = f(Q, Pg, GDPPC, RFS, E85)$

Ethanol demand and ethanol price are treated as endogenous in the equilibrium of ethanol demand Q and supply y.

A.5 GAMS Code

```
$TITLE Dissertation research code

*=============================================================
* Model-specific data defined here:

SET i Ethanol production  /Corn, Stover, swgrass, poplar, Wood,other/
SET j Ethanol i production input factor  /fs, oth/;
SET   u /2009*2030/;

* loading data-------------------------------------------------------
Table input(u,i,j)  input value of unit ethanol i
        corn.fs     stover.fs    swgrass.fs   poplar.fs    wood.fs  other.fs
2009      1.481       0.069        0.403        0.393       0.398    0.093
2010      1.489       0.069        0.398        0.388       0.403    0.093
2011      1.378       0.069        0.616        0.600       1.022    0.093
2012      1.548       0.070        0.608        0.592       1.017    0.094
2013      1.389       0.070        0.600        0.585       1.056    0.090
2014      1.641       0.070        0.593        0.578       1.042    0.088
2015      1.330       0.072        0.585        0.570       1.081    0.109
2016      1.525       0.120        0.640        0.623       1.253    0.156
2017      1.271       0.123        0.632        0.616       1.297    0.153
2018      1.408       0.123        0.625        0.609       1.270    0.149
2019      1.223       0.125        0.617        0.601       1.304    0.159
2020      1.337       0.125        0.610        0.595       1.288    0.165
2021      1.233       0.183        0.661        0.644       1.403    0.232
2022      1.337       0.207        0.676        0.659       1.393    0.260
2023      1.217       0.207        0.669        0.652       1.423    0.296
2024      1.273       0.206        0.661        0.645       1.412    0.314
2025      1.307       0.206        0.654        0.638       1.420    0.320
2026      1.210       0.208        0.654        0.638       1.643    0.267
2027      1.293       0.209        0.654        0.638       1.643    0.291
2028      1.223       0.211        0.654        0.638       1.680    0.308
2029      1.297       0.212        0.654        0.638       1.687    0.313
2030      1.213       0.214        0.654        0.638       1.720    0.307

+         corn.oth    stover.oth   swgrass.oth  poplar.oth   wood.oth  other.oth
2009      0.551       1.175        1.175        1.249        1.249     1.069
2010      0.551       1.101        1.101        1.170        1.170     1.069
2011      0.551       1.027        1.027        1.091        1.091     1.069
```

2012	0.551	0.953	0.953	1.012	1.012	1.069
2013	0.551	0.878	0.878	0.933	0.933	1.069
2014	0.551	0.804	0.804	0.854	0.854	1.069
2015	0.551	0.730	0.730	0.776	0.776	1.069
2016	0.551	0.730	0.730	0.776	0.776	0.972
2017	0.551	0.730	0.730	0.776	0.776	1.646
2018	0.551	0.730	0.730	0.776	0.776	1.967
2019	0.551	0.730	0.730	0.776	0.776	2.092
2020	0.551	0.730	0.730	0.776	0.776	2.085
2021	0.551	0.730	0.730	0.776	0.776	2.046
2022	0.551	0.730	0.730	0.776	0.776	2.011
2023	0.551	0.730	0.730	0.776	0.776	2.034
2024	0.551	0.730	0.730	0.776	0.776	1.986
2025	0.551	0.730	0.730	0.776	0.776	2.006
2026	0.551	0.730	0.730	0.776	0.776	1.881
2027	0.551	0.730	0.730	0.776	0.776	1.879
2028	0.551	0.730	0.730	0.776	0.776	1.939
2029	0.551	0.730	0.730	0.776	0.776	1.972
2030	0.551	0.730	0.730	0.776	0.776	2.005

;

Table ethanol(u,i) ethanol i quantity

	corn	stover	swgrass	Poplar	wood	other
2009	10.8	0	0	0	0.1	0.001
2010	11.73	0	0	0	0.3	0.000
2011	12.26	0.19	0.01	0	0.31	0.035
2012	12.86	0.35	0.03	0	0.56	0.069
2013	13.54	0.63	0.1	0	0.9	0.115
2014	14.13	0.94	0.25	0	1.37	0.187
2015	14.83	1.63	0.54	0	2.05	0.239
2016	14.81	2.34	0.95	0	2.49	0.443
2017	14.8	3.05	1.47	0	2.9	0.554
2018	14.78	3.52	2.29	0.01	3.46	0.718
2019	15.15	4.22	3.14	0.01	3.8	0.834
2020	15.15	4.62	4.22	0.01	4.18	0.973
2021	15.15	5.65	5.48	0.01	4.65	1.215
2022	15.15	6.13	7.17	0.01	5.24	1.457
2023	15.15	5.73	7.53	0.77	4.56	1.410
2024	15.15	5.34	8.19	0.75	4.27	1.457
2025	15.15	5.21	8.67	0.68	4.01	1.427
2026	15.15	5.34	9.2	0.69	3.16	1.596

2027 15.15 5.04 9.35 1.04 2.98 1.593
2028 15.15 4.69 8.9 2.26 2.67 1.480
2029 15.15 4.46 8.92 2.67 2.52 1.431
2030 15.15 4.6 9.25 2.25 2.49 1.410

;

Parameter AEO(u) AEO projection

/
2009 12.6
2010 13.8
2011 15.1
2012 16.3
2013 17.2
2014 18.2
2015 19.1
2016 20.1
2017 21.0
2018 21.9
2019 22.9
2020 23.8
2021 24.8
2022 25.7
2023 27.0
2024 28.3
2025 29.7
2026 31.0
2027 32.3
2028 33.6
2029 34.9
2030 36.3

/;

PARAMETER

alp(i) Benchmark value shares of ethanol i production in total ethanol production,
beta (i, j) Benchmark value share of input j in ethanol i production,
theta substitution elasticity parameter on cost function for total ethanol

```
t(i)        tax rate for ethanol i
;


* Initializing benchmark----------------------------------------------------

PARAMETER

TETH0       Benchmark production of total ethanol ,
PTETH0      Benchmark Price of ethanol,
SMD0(i)    Benchmark production of ethanol,
PSMD0(i)   Benchmark Price of producing ethanol i,
PINP0(i,j) Benchmark price of input factor j,
INPT0(i,j) Benchmark input value share of factor j in producing ethanol i
TDEMD      Total demand for ethanol
;

ALIAS(i,k); ALIAS(j,m);

* Calibration---------------------------------------------------------------

PINP0(i,j) = 1;
INPT0(i,j)=input("2009",i,j)*ethanol("2009",i);

PSMD0(i) = sum(j, input("2009",i,j));
SMD0(i) = ethanol("2009",i);
TETH0=sum(k,ethanol("2009",k));
TDEMD = TETH0;
PTETH0=sum(k,SMD0(k)*PSMD0(k))/TETH0;

alp(i) = (PSMD0(i)*SMD0(i))/sum(k, PSMD0(k)*SMD0(k));
beta(i,j) = input("2009",i,j)/sum(m, input("2009",i,m));
theta=2;

t(i)=0;

parameter
dTETH(u),dPTETH(u),dSMD(u,i),dPSMD(u,i),dPINP(u,i,j),dINPT(u,i,j);


* defining model system-----------------------------------------------------
Variable
```

```
PTETH      Ethanol price
TETH       Total ethanol production
PSMD(i)   price of ethanol i
SMD(i)    Production of ethanol i
PINP(i,j)  price for j in ethanol i production
INPT(i,j)  demand for j in ethanol i production
sse        objective
;


Equation

EQCOST    ethanol unit cost function
EQSMD1    ethanol i production function
EQTETH1   toatl ethnaol production and ethanol i
*EQTETH2   total ethanol production
EQPSMD    ethanol i cost function
EQSMD2    Demand function for input j to produce ethanol i
*EQSMD3    upper bound for feedstock i
obj       objective function
;
***Determines PSMD e.g. Price of Ethanol
***SMD is the quantity of ethanol produced
EQUATION EQCOST;
EQCOST.. PTETH =E= PTETH0*sum(i, alp(i)*(PSMD(i)/PSMD0(i))**(1-theta) )**(1/(1-
theta) );

***Determines: SMD(i) e.g. Qunatity of Ethanol from each type of feedstock (i.e. i = corn,
wood, switch grass, etc.)
***PSMD(i) is the price of ethanol from each type of feedstock (i.e. i = corn, wood, switch
grass, etc.)
EQUATION EQSMD1;
EQSMD1(i).. SMD(i) =E=
SMD0(i)*(TETH/TETH0)*((PTETH/PTETH0)*(PSMD0(i)/PSMD(i)))**theta;

***Determines:
EQUATION EQTETH1;
EQTETH1..TETH =E= TDEMD;


***Determines: PSMD(i) e.g. cost of Ethanol from each type of feedstock (i.e. i = corn,
wood, switch grass, etc.)
```

```
***PSMD(i,j) is the price of input factor j in producing ethanol i (i.e. j = feedstock, labor,
capital, etc.)
EQUATION EQPSMD;
*EQPSMD(i).. PSMD(i) =E=PSMD0(i)*(sum(j, beta(i,j)*PINP(i,j)/PINP0(i,j)));
EQPSMD(i).. PSMD(i) =E=PSMD0(i)*(1+t(i))*(sum(j, beta(i,j)*PINP(i,j)/PINP0(i,j)));


***Determines: SMD2(i, j) e.g. Demand for factor j of ethanol (i)  (i.e.j=feedstock, labor,
capital elec, etc.)
EQUATION EQSMD2;
EQSMD2(i,j).. PINP0(i,j)*INPT(i,j) =E= PSMD0(i)*SMD(i)*beta(i,j);


Equation obj;
obj.. sse=E=0;

model Test /all/;
*-------------------------------------------------------------------------

*$ontext

loop(u,
test.holdfixed = 0 ;

PINP0(i,j) = 1;
INPT0(i,j)= input(u,i,j)*ethanol(u,i);

INPT.lo(i,j) = INPT0(i,j)*0;
INPT.up(i,j) = INPT0(i,j)*10;

PSMD0(i) = sum(j, input(u,i,j));
SMD0(i) = ethanol(u,i);
TETH0=sum(k,ethanol(u,k));
TDEMD = TETH0;
PTETH0=sum(k,SMD0(k)*PSMD0(k))/TETH0;

alp(i) = (PSMD0(i)*SMD0(i))/sum(k, PSMD0(k)*SMD0(k));
beta(i,j) = input(u,i,j)/sum(m, input(u,i,m));



TETH.l=TETH0;
```

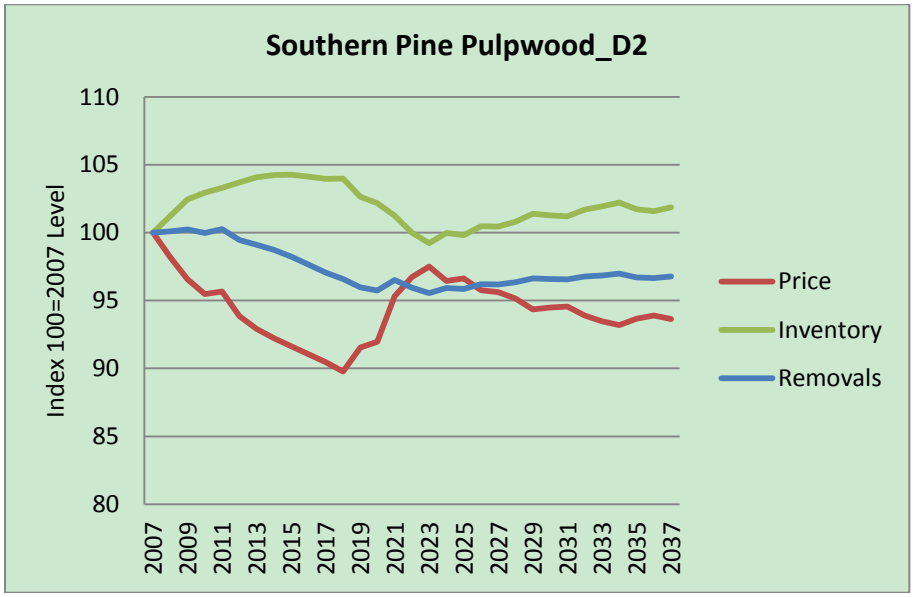
```
PTETH.l=PTETH0;
SMD.l(i)=SMD0(i);
PSMD.l(i)=PSMD0(i);
PINP.l(i,j)=PINP0(i,j);
INPT.l(i,j)=INPT0(i,j);


PINP.fx(i,j)=PINP0(i,j);


option limrow=0, limcol=0;


*TDEMD$(ord(u) = 14) = TETH0*1.05;
TDEMD = AEO(u);


*t("corn")$(ord(u) = 14)=0.238;
*t("wood")$(ord(u) = 14)=-0.25;


test.holdfixed = 1 ;
solve Test minimizing sse using nlp;

PINP.lo(i,j) = PINP0(i,j)*0;
PINP.up(i,j) = PINP0(i,j)*10;

dTETH(u) $TETH0 = (TETH.l/TETH0-1)*100;
dPTETH(u)$PTETH0=(PTETH.l/PTETH0-1)*100;
dSMD(u,i)$SMD0(i)=(SMD.l(i)/SMD0(i)-1)*100;
dPSMD(u,i)$PSMD0(i)=(PSMD.l(i)/PSMD0(i)-1)*100;
dPINP(u,i,j)$PINP0(i,j)=(PINP.l(i,j)/PINP0(i,j)-1)*100;
dINPT(u,i,j)$INPT0(i,j)=(INPT.l(i,j)/INPT0(i,j)-1)*100;

display dTETH,dPTETH,dSMD,dPSMD,dPINP,dINPT;



);

*$offtext
```

A.6 Abbreviations

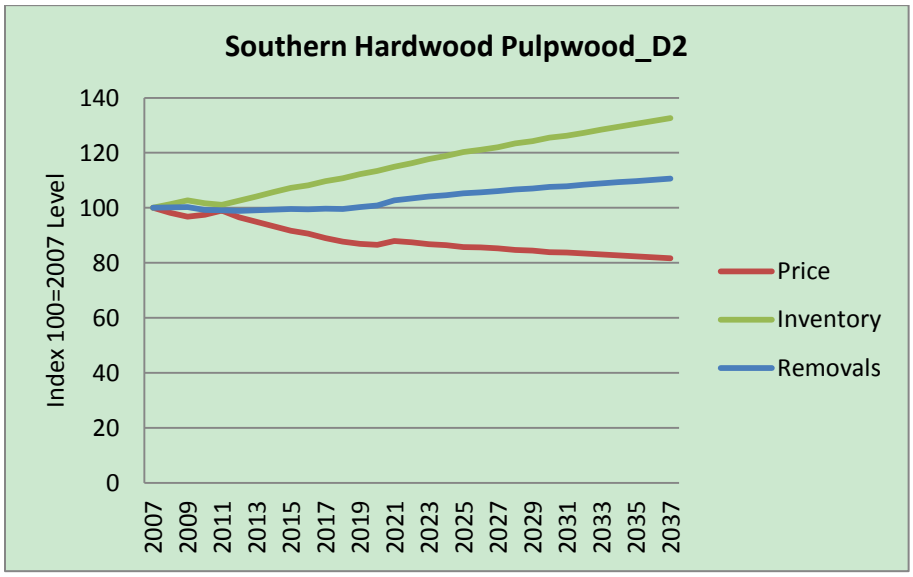
AEO: Annual Energy Outlook
BMP: Best Management Practices
CARB: The California Air Resources Board
CARD: Center for Agricultural and Rural Development
CGE: Computable General Equilibrium
CRP: Conservation Reserve Program
DAYCENT: Daily Century Model
EIA: Energy Information Administration
EISA: the US Energy Independence and Security Act
EPA: U.S. Environmental Protection Agency
FAPRI: Food and Agricultural Policy Research Institute
FASOM: Forest and Agricultural Sector Optimization Model
FIA: Forest Inventory and Analysis Program
GFPM: Global Forest Products Model
GHG: Greenhouse Gas
GREET: Greenhouse Gases, Regulated Emissions, and Energy Use
GTAP: Global Trade Analysis Project
GTM: Global Timber Model
ILUC: Indirect Land-use change
IMPLAN: Impact Analysis for Planning
IPCC : Intergovernmental Panel on Climate Change
KLUM: Kleines Land Use Model
LCA: Lifecycle Analysis
LCFS: Low Carbon Fuel Standards
LUC: Land-use change
MFM: Multi-Feedstock Model
MODIS: Moderate Resolution Imaging Spectoradiometer
NEMS: National Energy Modeling System
NPRM/NOPR: Notice of Proposed Rulemaking
NRCS: Natural Resource Conservation Service
PE: Partial Equilibrium
POLYSYS: Policy Analysis System
RFA: Renewable Fuel Association
RFS2: Renewable Fuel Standards signed in 2007
RPS: Renewable Portfolio Standards
SRTS: Sub-Regional Timber Supply Model
USDA: U.S. Department of Agriculture
USFPM: US Forest Products Module
WEPS: Wind Erosion Prediction System

Appendix B

B.1 Figures of SRTS results on pulpwood price, inventory, and removals

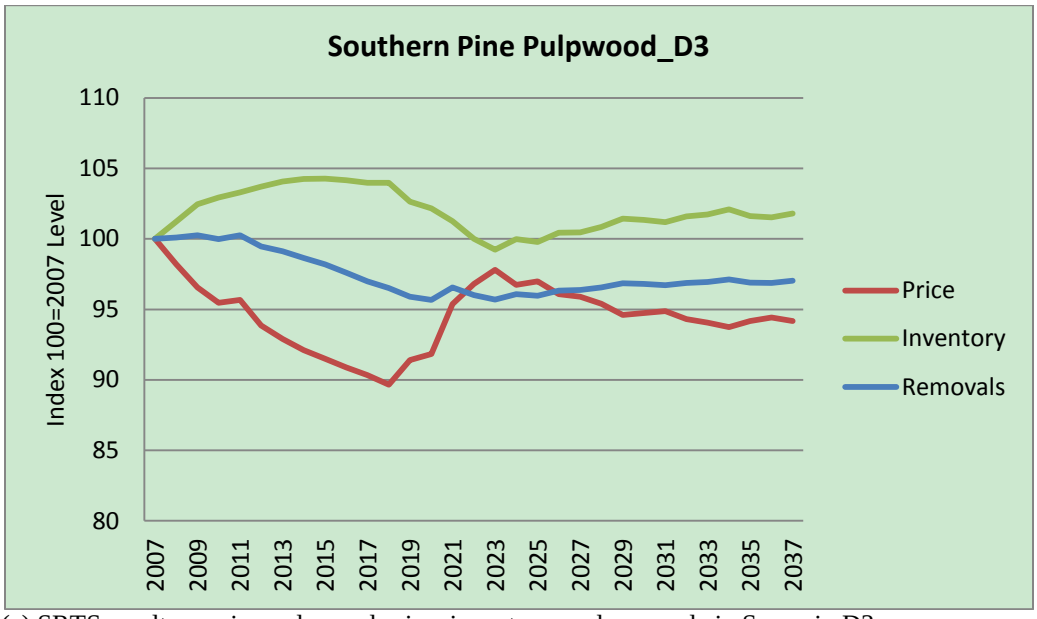


(a) SRTS results on pine pulpwood price, inventory, and removals in Scenario D2

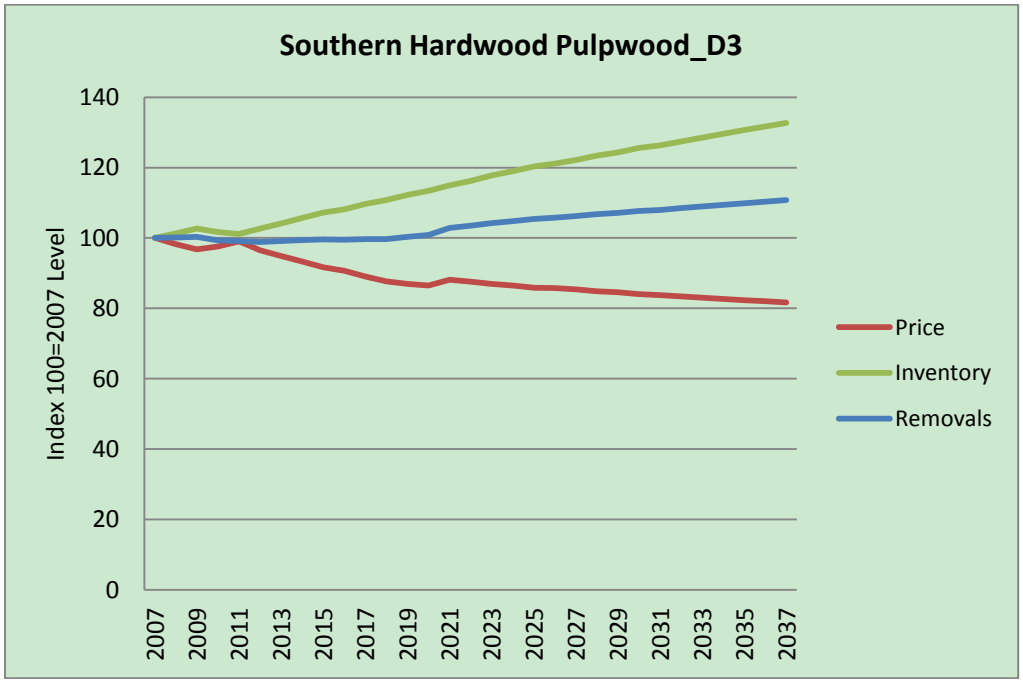


(b) SRTS results on pulpwood price, inventory, and removals in Scenario D2

Table B.1 1 Figures of SRTS results on pulpwood price, inventory, and removals in Scenario D2

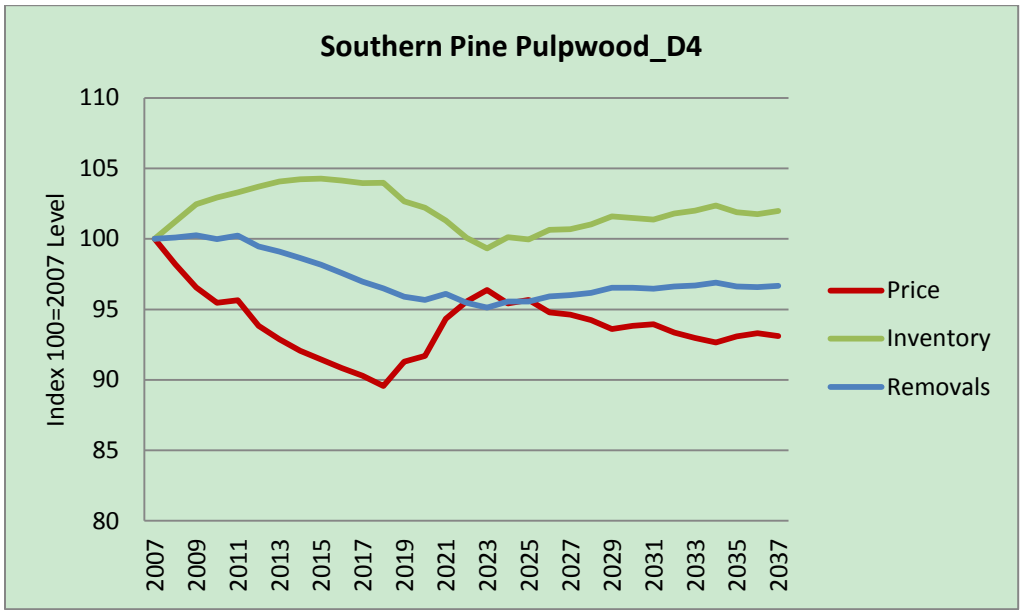


(a) SRTS results on pine pulpwood price, inventory, and removals in Scenario D3

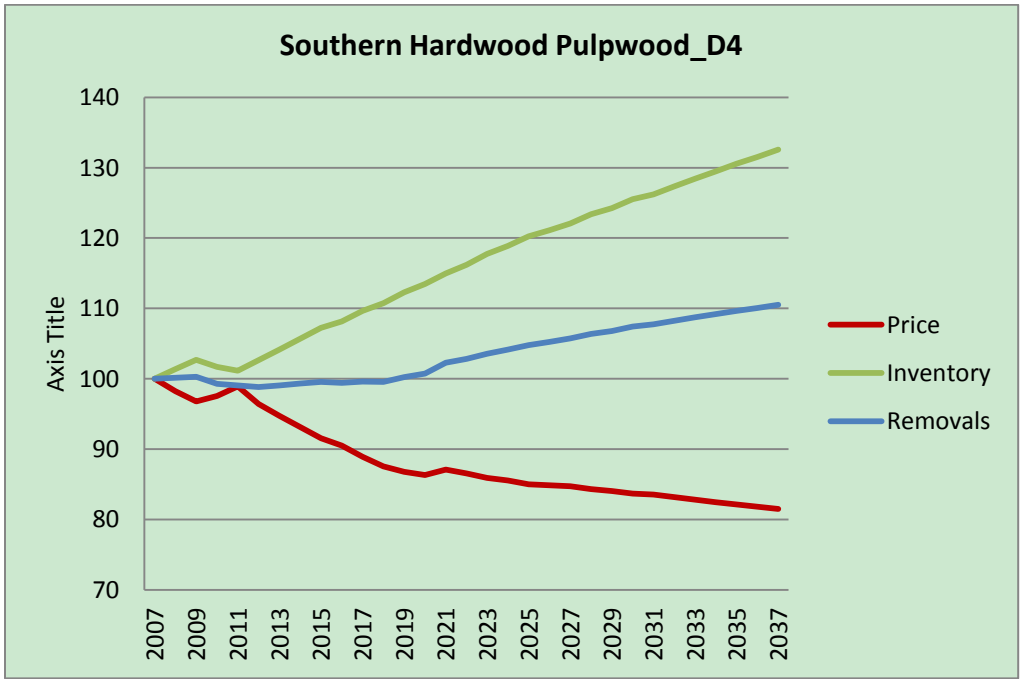


(b) SRTS results on hardwood pulpwood price, inventory, and removals in Scenario D3

Table B.1 2 Figures of SRTS results on pulpwood price, inventory, and removals in Scenario D3



(a) SRTS results on pine pulpwood price, inventory, and removals in Scenario D4



(b) SRTS results on hardwood pulpwood price, inventory, and removals in Scenario D4

Table B.1 3 Figures of SRTS results on pulpwood price, inventory, and removals in Scenario D4

B.2 Maps of pulpwood inventory change by species and state

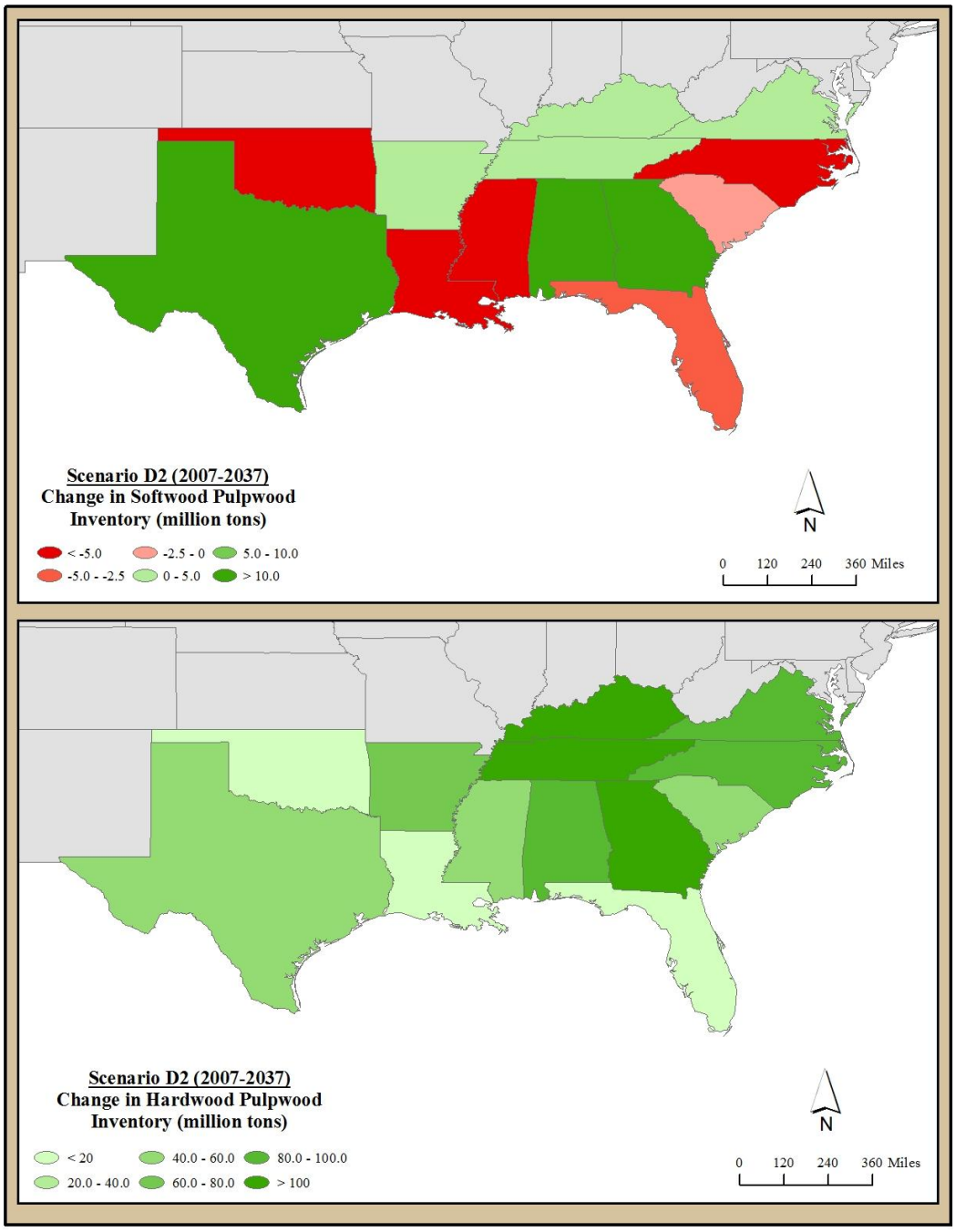


Figure B.2 1 Maps of pulpwood inventory change by species and state under Scenario D2

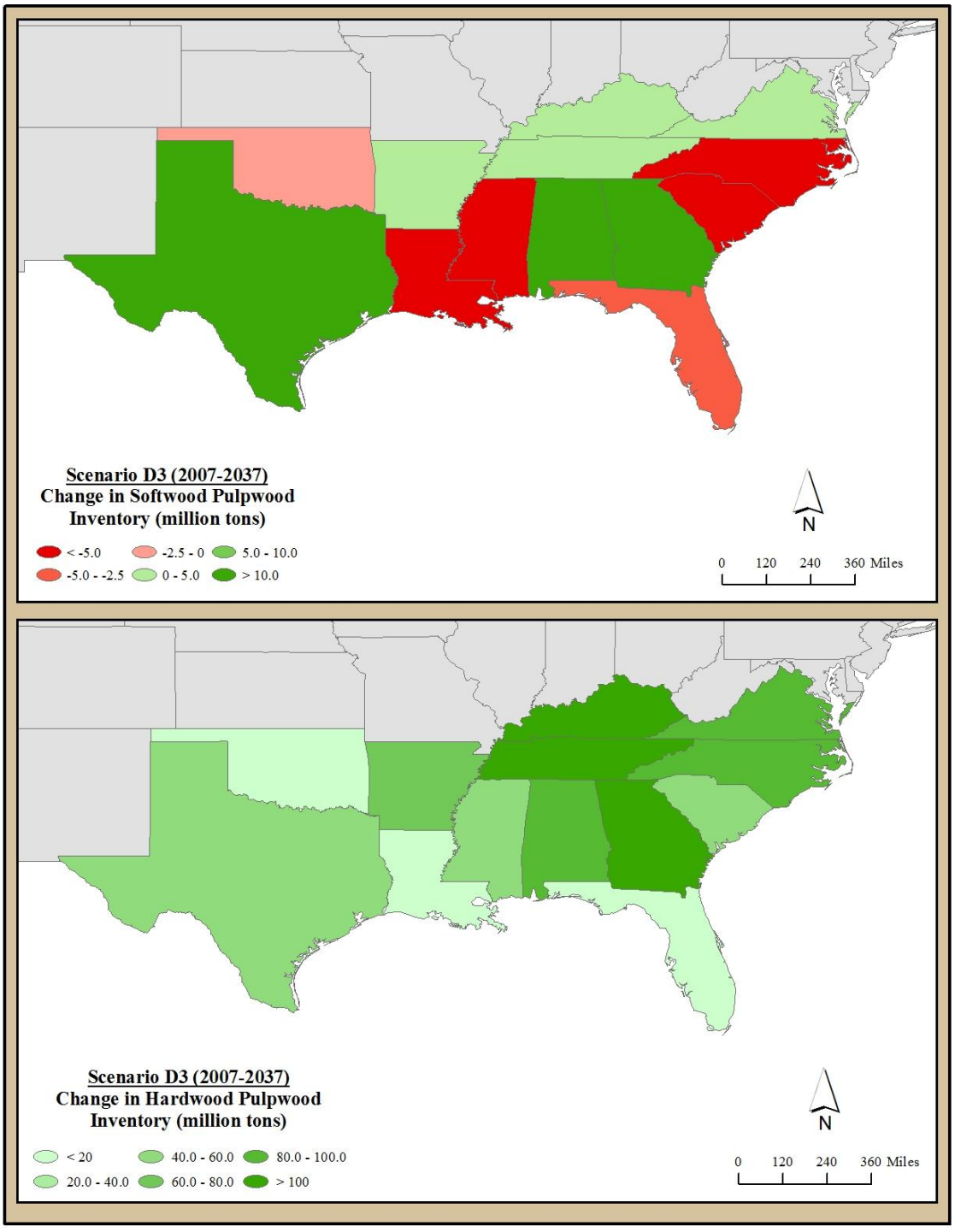


Figure B.2 2 Maps of pulpwood inventory change by species and state under Scenario D3

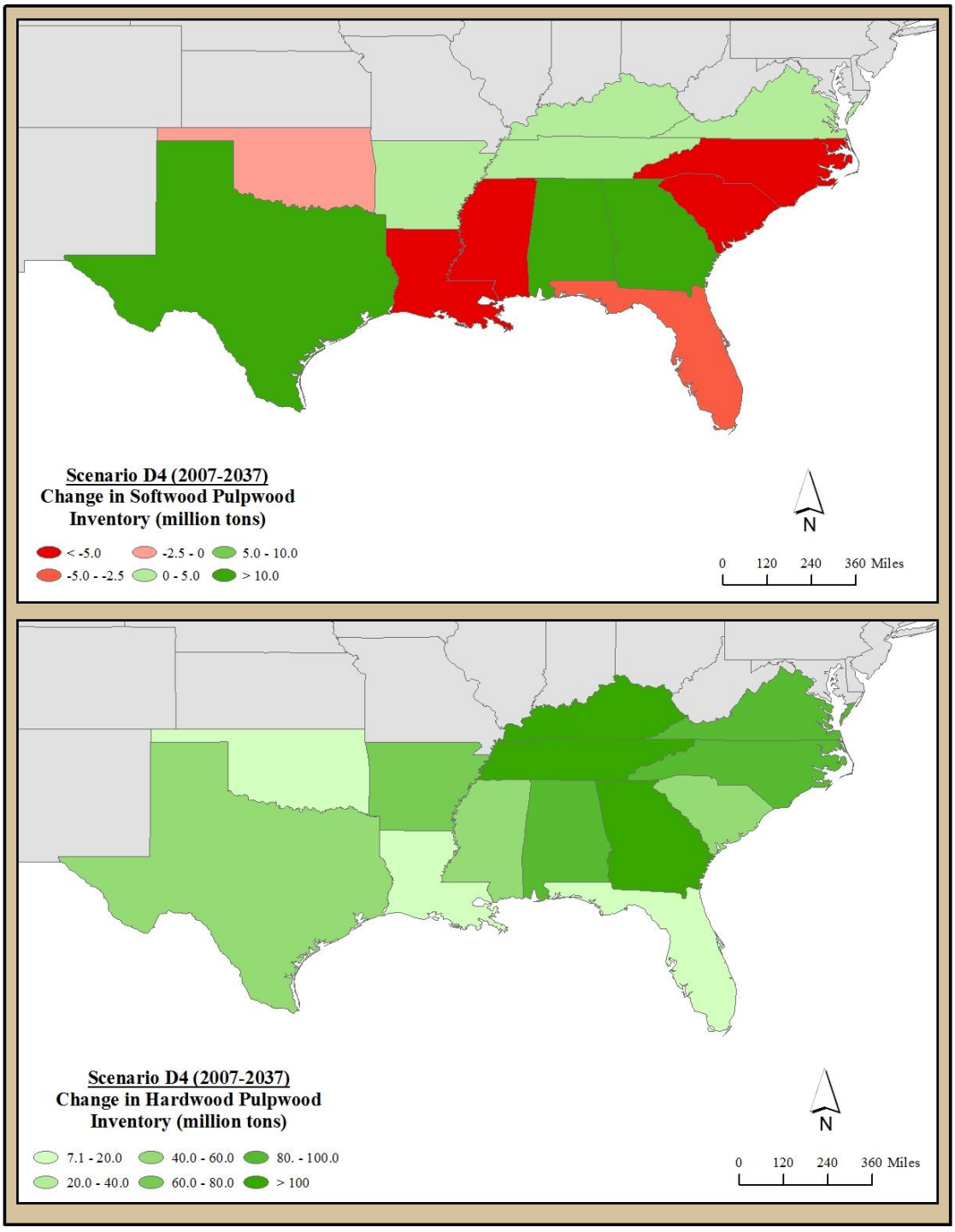


Figure B.2 3 Maps of pulpwood inventory change by species and state under Scenario D4

B.3 Figures of logging residues by species

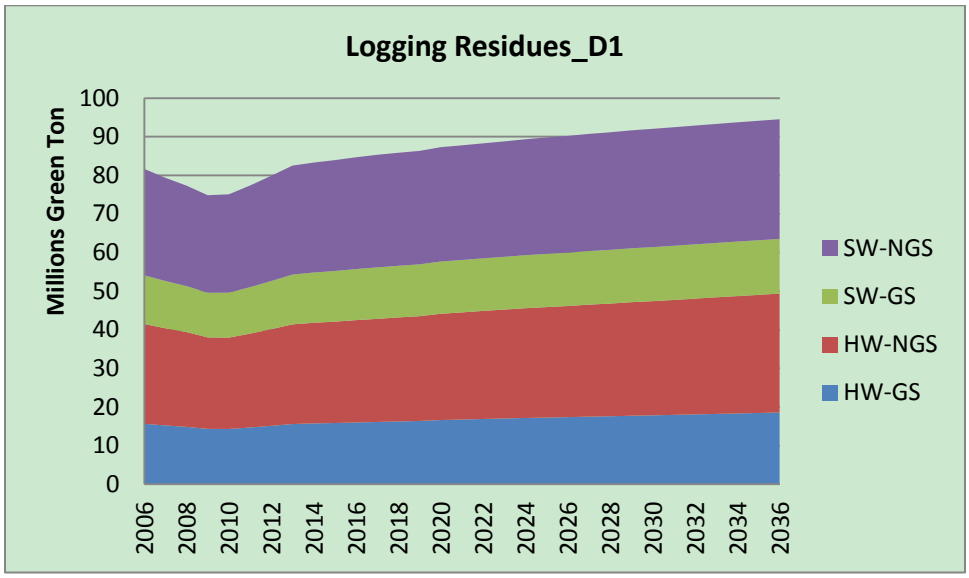


Figure B.3 1 Logging residues by species under scenario D1

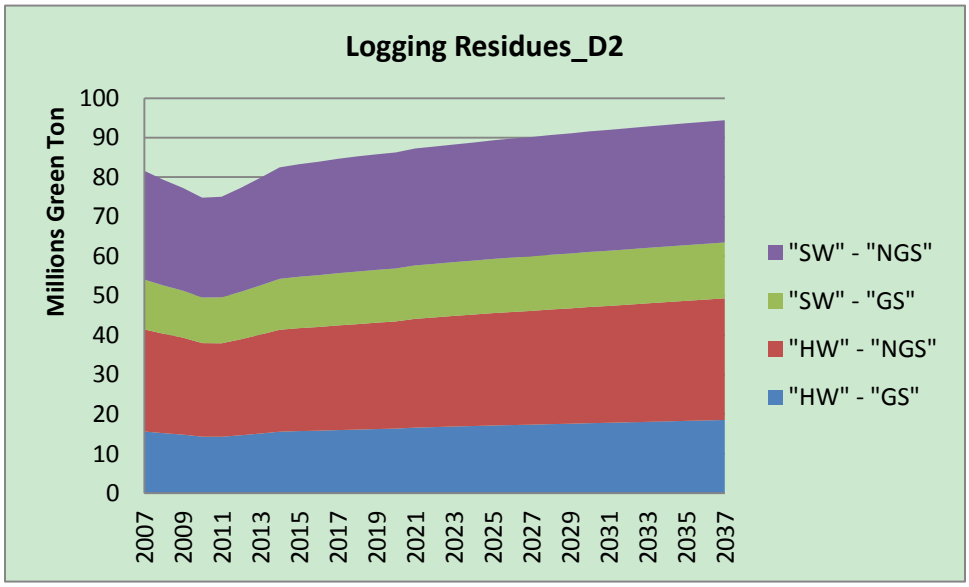


Figure B.3 2 Logging residues by species under scenario D2

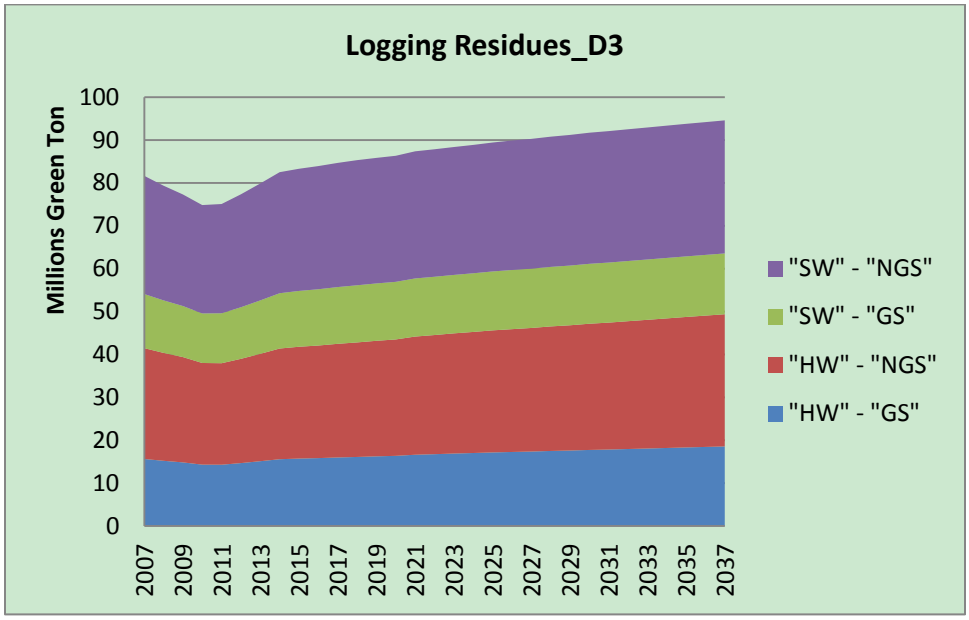


Figure B.3 3 Logging residues by species under scenario D3

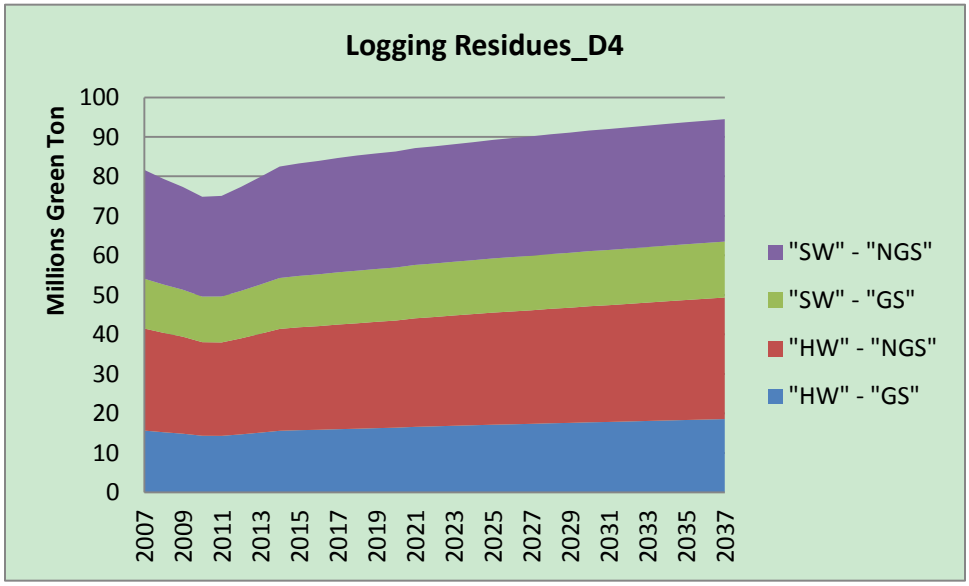


Figure B.3 4 Logging residues by species under scenario D4

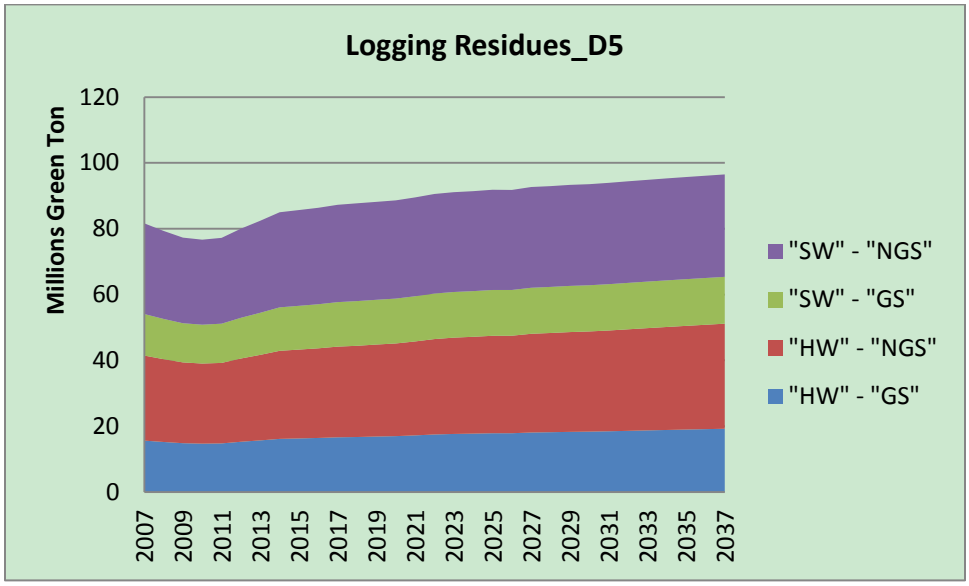


Figure B.3 5 Logging residues by species under scenario D5

B.4 Figures of forest land management type

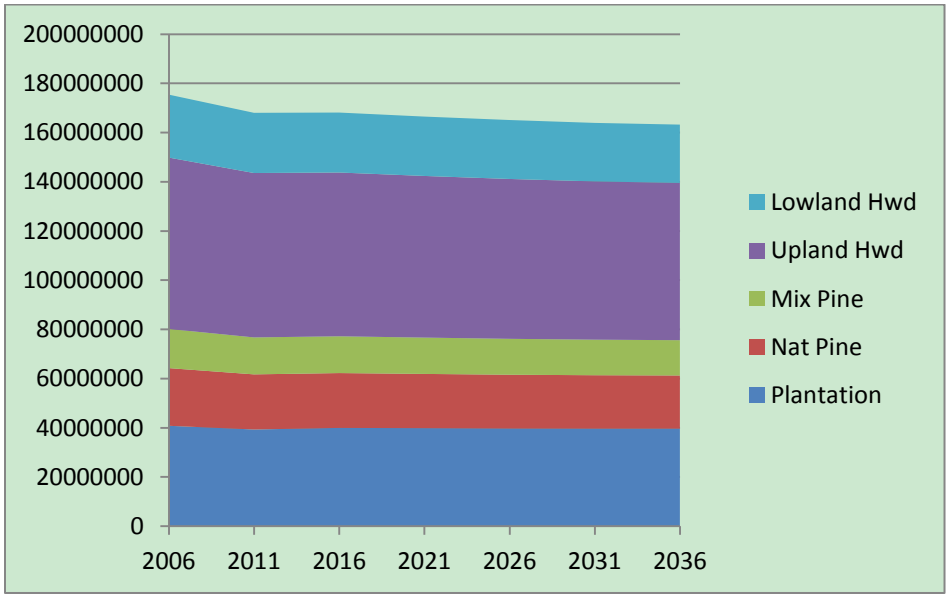


Figure B.4 1 Forest land management type under Scenario D1

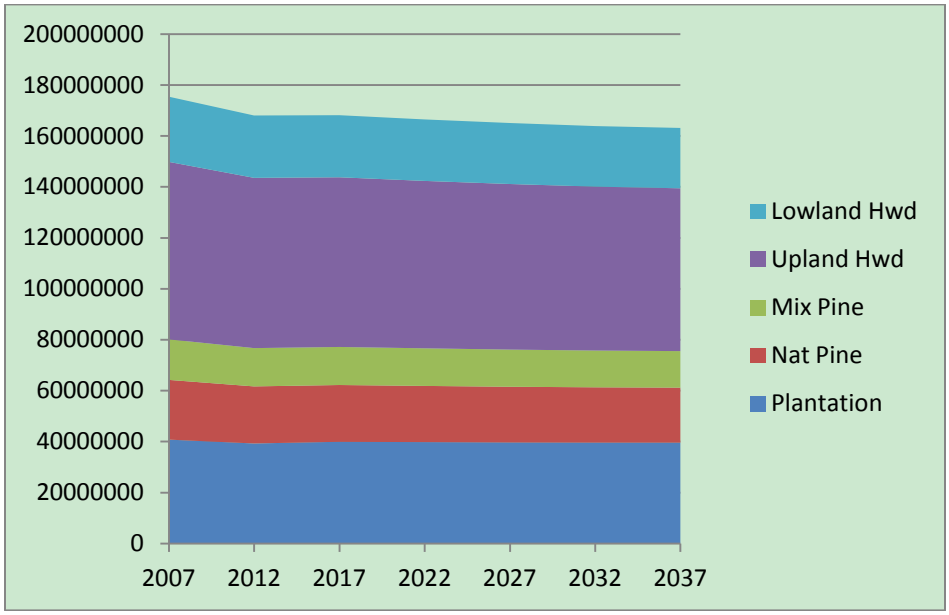


Figure B.4 2 Forest land management type under Scenario D2

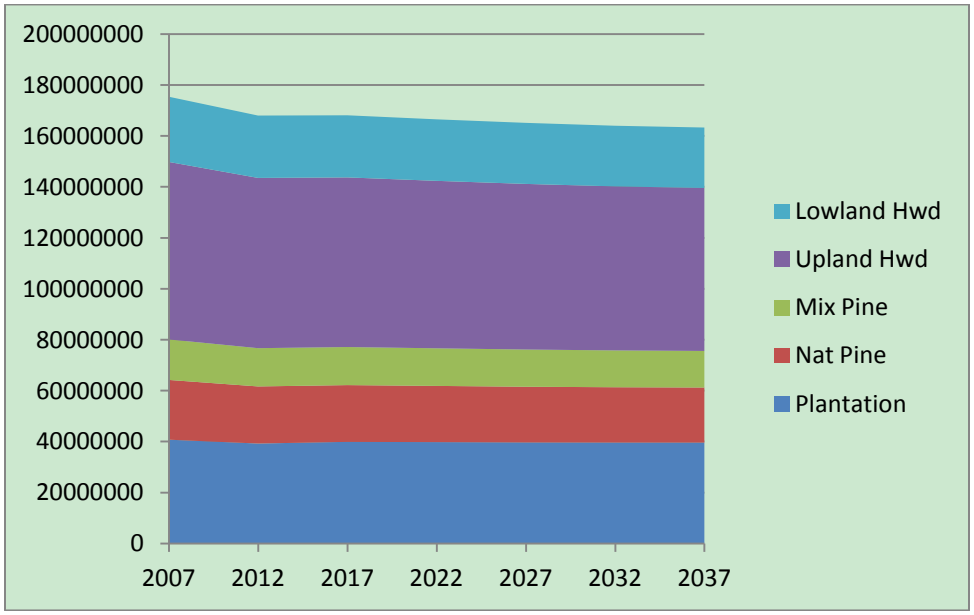


Figure B.4 3 Forest land management type under Scenario D3

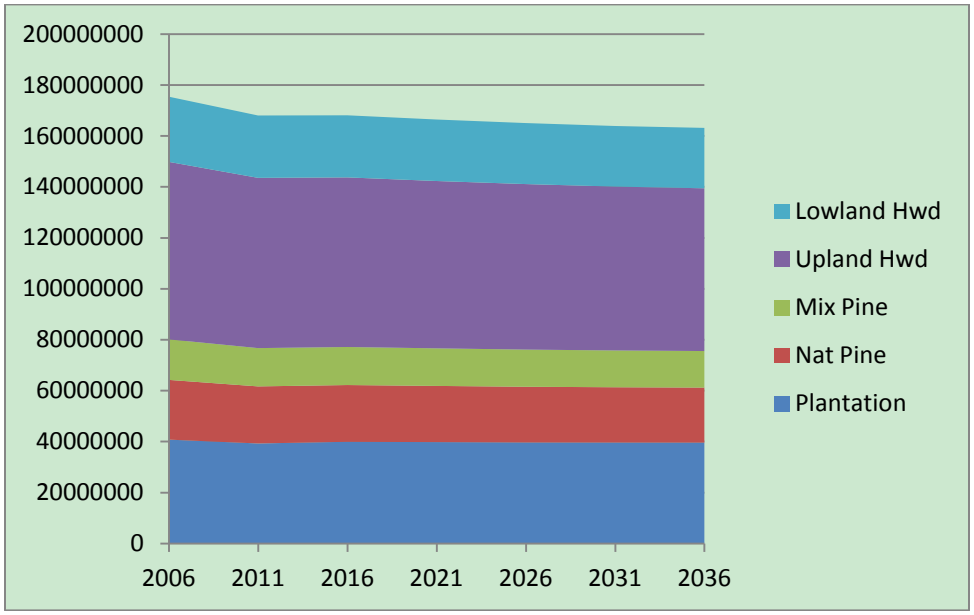


Figure B.4 4 Forest land management type under Scenario D4

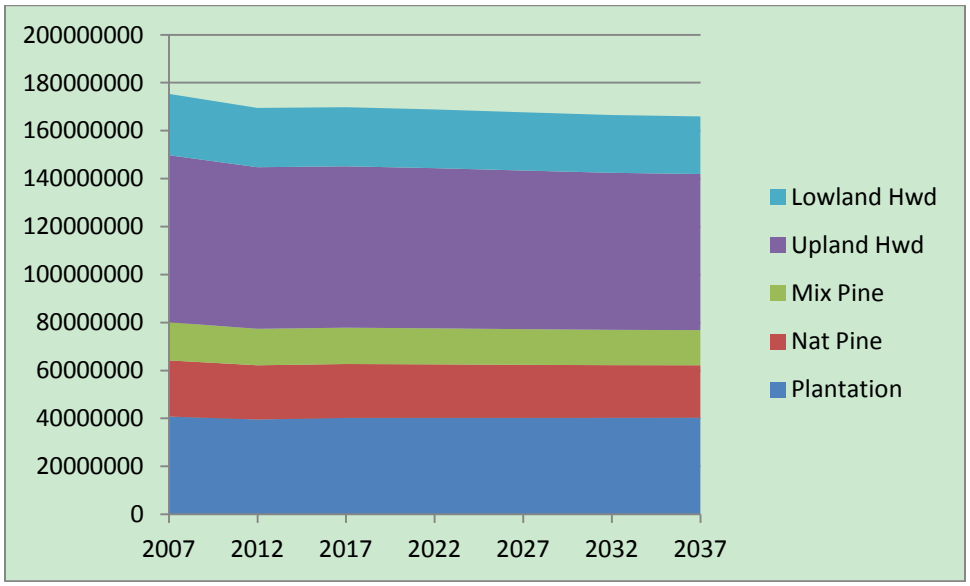


Figure B.4 5 Forest land management type under Scenario D5

B.5 Figures of forest age structure

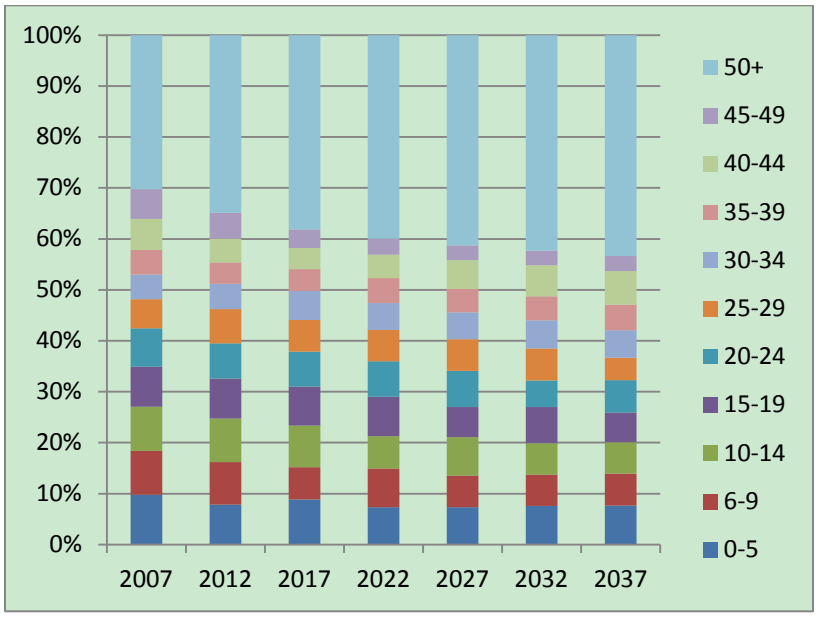


Figure B.5 1 Forest age structure over time under scenario D1

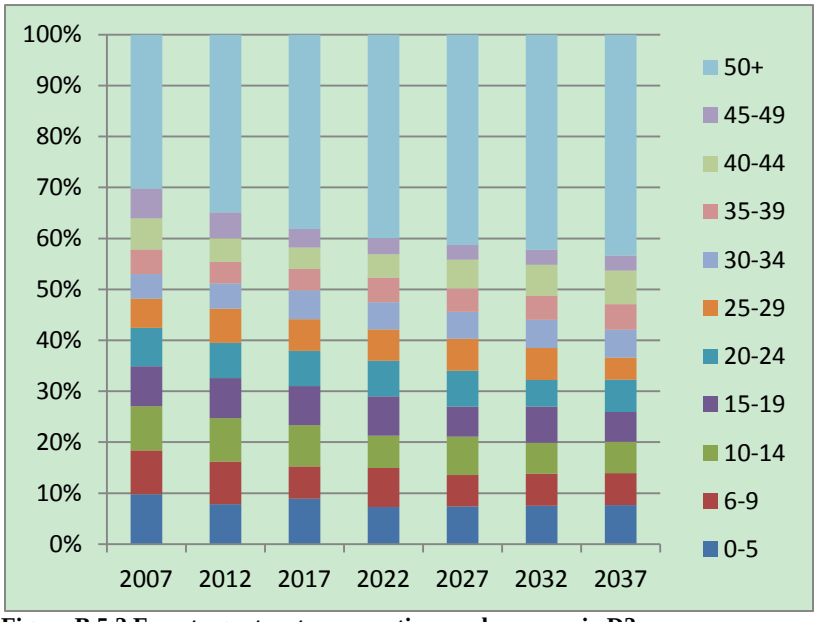


Figure B.5 2 Forest age structure over time under scenario D2

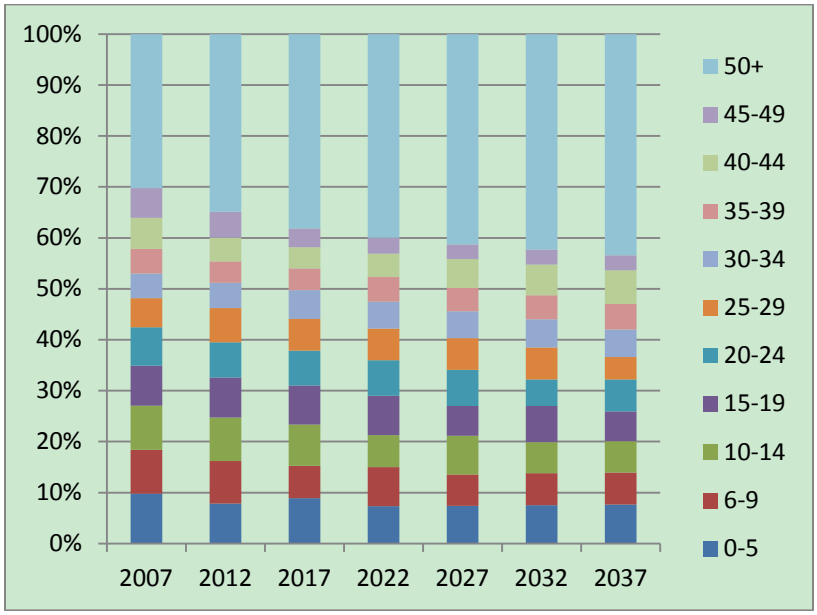


Figure B.5 3 Forest age structure over time under scenario D3

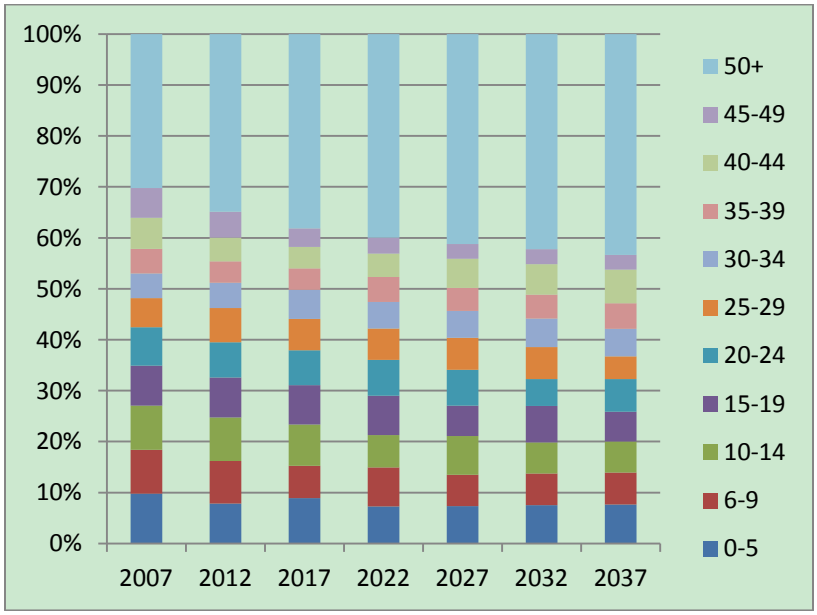


Figure B.5 4 Forest age structure over time under scenario D4

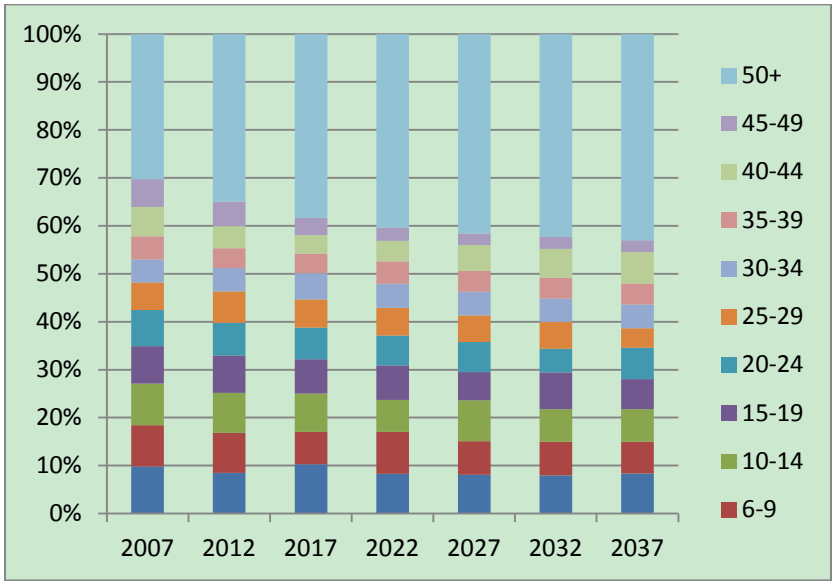


Figure B.5 5 Forest age structure over time under scenario D5

B.6 Figures of POLYSYS results on pulpwood market without SRTS

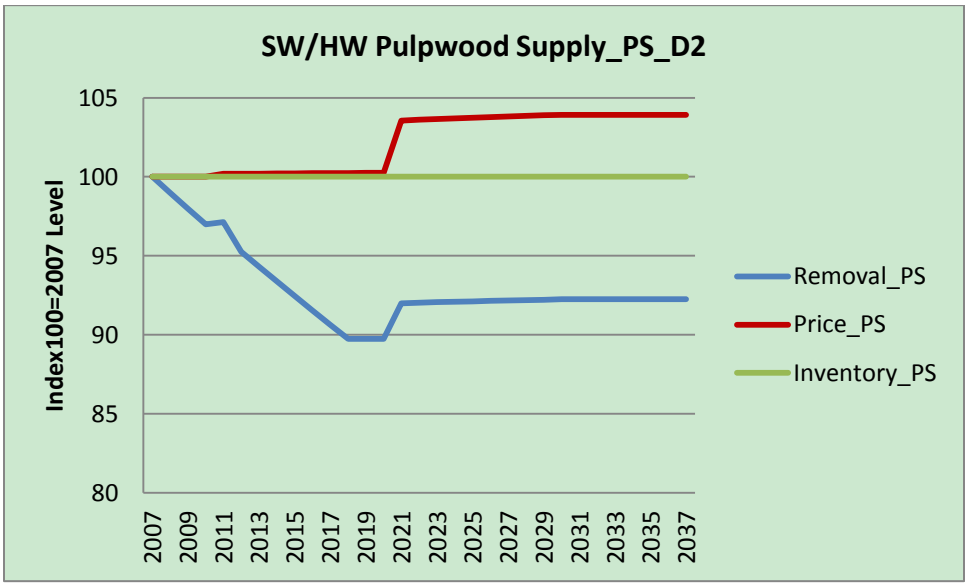


Figure B.6 1 POLYSYS results on pulpwood market without SRTS under D2

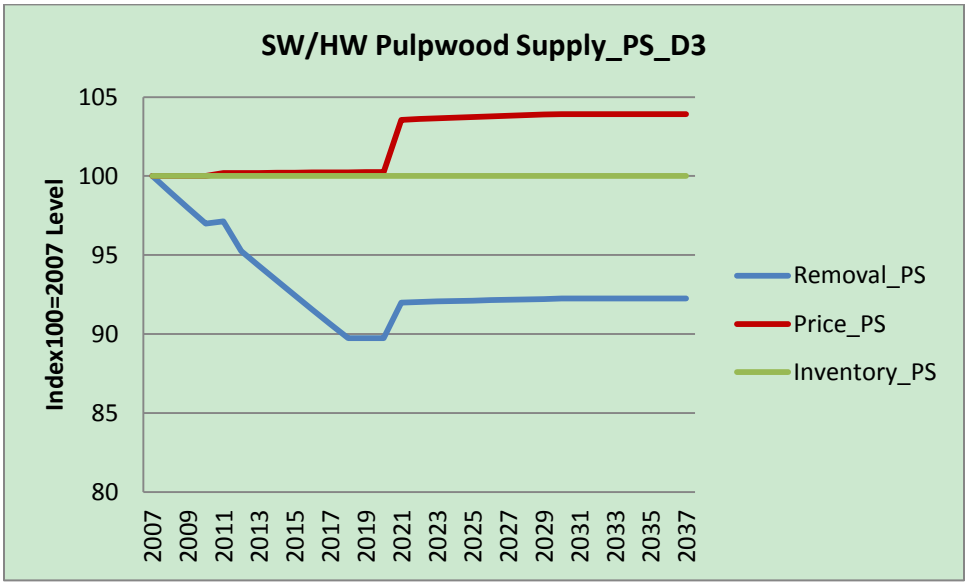


Figure B.6 2 POLYSYS results on pulpwood market without SRTS under D3

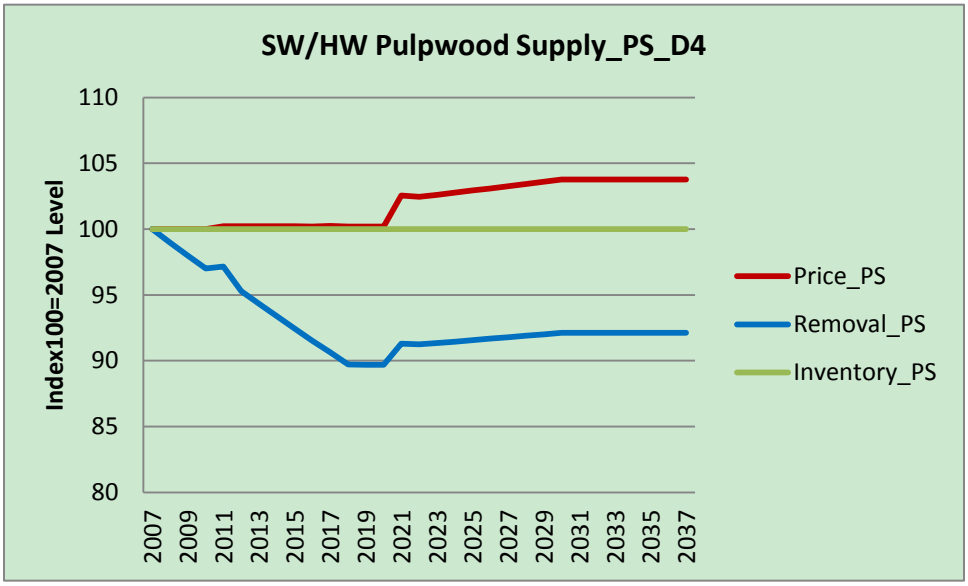


Figure B.6 3 POLYSYS results on pulpwood market without SRTS under D4