ENVIRONMENTAL AND ECONOMIC SUITABILITY OF FOREST BIOMASS-BASED BIOENERGY PRODUCTION IN THE SOUTHERN UNITED STATES

By

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To almighty and all his noble manifestations around me!

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This study attempts to ascertain the environmental and economic suitability of utilizing forest biomass for cellulosic ethanol production in the Southern United States. The study is divided into six chapters. The first chapter details the background and defines the relevance of the study along with objectives. The second chapter reviews the existing literature to ascertain the present status of various existing conversion technologies. The third chapter assesses the net energy ratio and global warming impact of ethanol produced from slash pine (*Pinus elliottii* Engelm.) biomass. A life-cycle assessment was applied to achieve the task. The fourth chapter assesses the role of emerging bioenergy and voluntary carbon markets on the profitability of non-industrial private forest (NIPF) landowners by combining the Faustmann and Hartmann models. The fifth chapter assesses perceptions of four stakeholder groups (Non-Government Organization, Academics, Industries, and Government) on the use of forest biomass for bioenergy production in the Southern United States using the SWOT-AHP (Strength, Weakness, Opportunity, and Threat - Analytical Hierarchy Process) technique. Finally, overall conclusions are made in the sixth chapter.

Results indicate that currently the production of cellulosic ethanol is limited as the production cost of cellulosic ethanol is higher than the production cost of ethanol derived from corn. However, it is expected that the production cost of cellulosic ethanol will come down in the future from its current level due to ongoing research efforts. The total global warming impact of E85 fuel (production and consumption) was found as 10.44 tons where as global warming impact of an equivalent amount of gasoline (production and consumption) was 21.45 tons. This suggests that the production and use of ethanol derived from slash pine biomass in the form of E85 fuel in an automobile saves about 51% of carbon emissions when compared to gasoline. The net energy ratio of ethanol produced at the mill was found to be 3.2. The unit cost of production of ethanol was estimated to be $2.05 per gasoline gallon energy equivalent. The study also found that the emerging bioenergy and voluntary carbon markets will significantly increase land expectation values and, thus, the profitability of landowners. Results suggest that the optimal rotation age is insensible to alternate management scenarios. Finally, it was found that all stakeholder groups perceive that the overall benefits of forest biomass-based bioenergy development were higher than its weaknesses.

CHAPTER 1
INTRODUCTION TO THE STUDY

Background

The United States is the largest consumer of gasoline in the world. About 363 million gallons/day of gasoline were consumed in 2008 which was about 26% more than the total gasoline consumed in 1985 (EIA 2009a). About 110 and 62 million barrels of gasoline were imported and exported in 2008, respectively (EIA 2009b). Based on these numbers, it can be easily deduced that the net imported gasoline accounted for just 1.51% of total gasoline consumed in the country in 2008. This implies that the country is almost self sufficient in meeting the domestic demand for gasoline. However, this is not true, as it does not account for the gasoline which was refined from imported crude oil within the country.

About 3,581 million barrels of crude oil were imported into the country in the year 2008 which was 207% higher than the crude oil imported in 1985. It was found that Canada, Mexico, Saudi Arabia, Venezuela, Nigeria, and Iraq supplied about 20%, 12%, 16%, 11%, 10%, and 7% of total crude oil imported in 2008, respectively (EIA 2009c). As a barrel of crude oil (42 gallons) yields 18.56 gallons of gasoline (EIA 2009d), therefore 183 million gallons/day of gasoline were produced from imported crude oil in 2008. This implies that 52% of the total gasoline consumed in the country in 2008 was produced from imported crude oil after subtracting net quantities of imported gasoline.

The prime reason for increasing crude oil imports is the continuously declining domestic crude oil production in the United States. For example, about 1,914 million barrels of crude oil were produced in the United States in 2008 out of which about 5% was produced from offshore oil wells and remaining was produced from oil wells located on the main land. This total production of crude oil was about 40% less than the crude oil produced in 1985 (EIA 2009e). This implies that the country is increasingly becoming dependent on foreign countries to meet the domestic demand for various petroleum products like gasoline, diesel, heating oil, jet fuel, chemical feedstocks, asphalt, and other products.

Dependence on foreign countries for crude oil and other petroleum products increases the vulnerability of the country towards price fluctuations in the international energy market and global conflicts. Additionally, use of various petroleum products raises concern about the emission of various greenhouse gases which are responsible for global warming. For instance, it was reported that the consumption of a gallon of gasoline in an automobile releases 19.56 pounds of carbon dioxide (a primary greenhouse gas) into the atmosphere (EIA 2009f). Therefore, it can be deduced that about 7,101 million pounds of carbon dioxide/day was released into the atmosphere due to daily consumption of gasoline in 2008 alone. Note that the transportation sector alone contributed about 24% of all the carbon dioxide emissions in 2008 at the national level. The contribution of transportation sector was second highest (2,220 million tons) proceeded by electrical sector (2,670 million tons) and followed by industrial (1,808 million tons), residential (1,378 million tons), and commercial sectors (1,199 million tons) of economy (EIA 2009g).

Policy makers have launched several initiatives to ensure energy independence and a reduction in the emission of greenhouse gases. Foremost among all the initiatives is to increase the use of various renewable energy sources like solar, wind, geothermal, hydropower, and biopower found in the country. It is expected that the use of renewable energy can help the country in reducing greenhouse gas emissions and in achieving energy independence. It is also believed that this will propel economic development in the country by creating local jobs.

Renewable Energy Resources in the United States

The potential of various renewable energy sources to meet the growing energy demand of the nation is enormous. For example, ACORE (2007) reported that about 635 GW of power can be produced from various renewable sources by the end of year 2025 out of which power from wind, solar, hydro, geothermal, and biomass could contribute about 248,164, 23,100, and 100 GW, respectively. Note that the total installed electricity generation capacity in 2008 was about 1,088 GW (EIA 2009h).

The section below summarizes the present status of various renewable energy sources in the country.

Solar energy: The solar energy is by far the Earth's most available energy source and is abundantly available in the United States. Figure 1-1 shows the distribution of solar energy available across the United States (EIA 2009i). Solar energy can be used for both heating and electricity generation. At yearend 2008, the United States had about 8,800 MW of installed solar capacity. This included about 1,100 MW of photovoltaics, 418 MW of utility-scale concentrating solar power, at least 485 MW_{Th} of solar water heating systems, and over 7,000 MW_{Th} of solar pool heating systems (SEIA 2009). It is expected that use of solar energy to meet nation's energy needs will further grow due to the policy support provided by the federal government in the form of the Emergency Economic Stabilization Act of 2008. This act extends the 30% solar investment tax credit for eight years, lifts the cap for residential photovoltaic installations, allows application of the tax credits against the alternative minimum taxes, and removes the prohibition against utilities' use of the solar investment tax credits (SEIA 2008).

Wind Energy: The total installed capacity of wind power in the country by yearend 2009 was about 34,863 MW. Figure 1-2 shows the distribution of wind energy production in the United States (EERE 2009a). As observed, Texas (9,403 MW) and California (2,798 MW) are prime producers of the wind power in the country followed by Iowa (3,604) and Minnesota (1,810 MW). It is expected that existing tax benefits and various other policy instruments (e.g., Renewable Portfolio Standards[1]) will further help in increasing the wind-based power generation in the country.

Geothermal Energy: The Earth's heat can be utilized to produce electricity. The total potential of geothermal energy by the year 2050 in the United States is estimated to be about 12,486 GW_e and 1,249 GW_e at 20% and 2% heat recovery rate, respectively (MIT 2006). In 2008 about 0.358 quadrillion Btu of energy was extracted from geothermal sources which was only about 0.36% of total energy consumed in the country in the same year (EIA 2009j).

Hydro Power: The total production of hydro electricity was about 2.453 quadrillion Btu in 2008 (EIA 2009j). This corresponds to about 2.47% of total electricity produced in the nation in 2008. It is expected that with an emphasis on micro-hydel projects, the role of hydro power in meeting the future energy needs of the nation will become more important. Additionally, research is going on in developing commercially viable technologies to extract energy contained in ocean and tidal waves. It is hoped that

[1] The Renewable Portfolio Standard is a regulation which mandates utilities to source part of their total electricity generation from renewable energy sources like wind, solar, geothermal, hydro, or biomass. The percentage of renewable energy varies from state to state. For example, the Renewable Portfolio Standard for the state of California is 33% by 2020 and for the state of New York is 24% by 2013.

these technologies will be developed soon. This will further underline the importance of hydro power in meeting the future energy needs of the nation in a sustainable manner.

Biopower: Various biomass feedstocks are used for producing electricity. In the year 2007, about 28,919 million kWh of electricity was produced using biomass out of which 95% was consumed by a single sector of economy only i.e., paper and allied products (EIA 2009k). It is expected that in the presence of suitable incentives (e.g., Renewable Portfolio Standards) the electricity production from biomass will go up as several companies are building large scale biomass-based power plants to produce electricity. For example, Gainesville Regional Utilities is planning to build a 100 MW power plant at Gainesville, Florida which will utilize biomass to produce electricity (GRU 2009).

The above analysis of various renewable energy sources gives an impression that promoters of renewable technologies are interested in only producing electricity and heat to meet future energy demand. However, recently a lot of emphasis is being made on utilizing various biomass feedstocks to produce ethanol and biodiesel with an objective of reducing country's dependence on foreign energy sources. It was also reported that renewable fuels can contribute about 30% to 40% of total petroleum consumption in 2025 (ACORE 2007). This study focuses on ethanol, therefore only details of ethanol derived from various biomass feedstocks in general and forestry feedstocks in particular will be discussed from hereafter.

Ethanol Production in the United States

Ethanol production got a big support in the country when the Congress passed the Federal Clean Air Act Amendments of 1990 through which the use of reformulated gasoline in ozone nonattainment areas was made mandatory beginning in 1995. The

Congress specified that reformulated gasoline should contain 2% oxygen by weight. Ethanol and Methyl Tertiary Butyl Ether (MTBE) were the two most commonly used oxygenates in initial years. However, several states banned the use of MTBE and as a result ethanol became the oxygenate of choice in the reformulated gasoline program.

The Energy Policy Act of 2005 promulgated a nationwide renewable fuels standard (RFS) in which it was mandated to produce 7.5 billion gallons of renewable fuels by the year 2012. A credit-trading program was also created in which a gallon of ethanol derived from cellulosic biomass or waste was assumed equal to 2.5 gallons of renewable fuel. Additionally, a program for the production of 250 million gallons of cellulosic ethanol by 2013 was also mentioned in the same act. Suitable tax incentives and various grants were also announced to attract investors and researchers in order to increase the success of the entire renewable fuel production program. Several states also announced several incentives (tax credits, subsidies, etc.) to promote ethanol production in their state.

The Energy Independence and Security Act of 2007 further redefined the RFS and mandated the production of at least 36 billion gallons of renewable fuel by the year 2022 of which 21 billion gallons was required to be obtained in the form of advanced biofuels.[2] It was also mentioned that out of 21 billion gallons of advanced biofuels, 16

[2] The term advanced biofuel means renewable fuel, other than ethanol derived from corn starch that has at least 50% less greenhouse gas emissions relative to baseline greenhouse gas emissions. This includes a) ethanol derived from cellulose, hemicellulose, or lignin; b) ethanol derived from sugar or starch (other than corn starch); c) ethanol derived from waste material, including crop residue, other vegetative waste material, animal waste, and food waste and yard waste; d) biomass-based diesel; e) biogas (including landfill gas and sewage waste treatment gas) produced through the conversion of organic matter from renewable biomass; f) butanol or other alcohols produced through the conversion of organic matter from renewable biomass; and g) other fuel derived from cellulosic biomass.

billion gallons should qualify as cellulosic biofuels.[3] The quantity of conventional renewable fuel i.e., ethanol derived from corn starch was capped at 15 billion gallons. In addition to both acts, ethanol production was also facilitated by the Food, Conservation, and Energy Act of 2008, which provided a subsidy of $1.01 for every gallon of cellulosic ethanol produced and $0.45/gallon on conventional biofuel.

Due to these various incentives provided by the federal and various state governments, ethanol production has increased substantially in recent years. For example, national ethanol production was only 175 million gallons in 1990, but jumped to 9,000 million gallons in 2008 (RFA 2009).

Feedstocks for Ethanol Production

Ethanol can be produced from several biomass feedstocks. These biomass feedstocks are either sourced from agricultural lands or forestlands. Currently, the majority of ethanol produced in the country comes from corn. Use of corn for ethanol production has raised concerns for food security (Mitchell 2009) and environmental sustainability (Pimentel and Patzek 2005). More recently, the impacts of land use change have been considered in calculating the net emission of greenhouse gases from biofuel production indicating that the conversion of grasslands, peat lands, tropical forests, and other intact ecosystems to grow energy feedstocks far outweighs the greenhouse gas offsets of burning biofuels rather than fossil fuels (Fargione 2008; Searchinger 2008). It has also been reported that devoting the entire nation's 2005 corn crop to ethanol production would have offset only about 12% of the gasoline consumed

[3] The term cellulosic biofuel means renewable fuel derived from any cellulose, hemicellulose, or lignin that is derived from renewable biomass and that has lifecycle greenhouse gas emissions that are at least 60% less than the baseline lifecycle greenhouse gas emissions.

in the same year (Hill 2006). Because of concerns associated with grain-based ethanol production, policy makers are emphasizing the use of various cellulosic feedstocks for ethanol production as manifested through the redefined RFS.

Several cellulosic feedstocks like corn stover, switchgrass, wheat residues, sugarcane, and processing residues, etc. can be obtained from agricultural lands. However, forestlands will also play a significant role in meeting the growing demand for cellulosic feedstocks to produce ethanol. Perlack et al. (2005) estimated that about 368 million dry tons of forestland-derived biomass can be utilized for bioenergy development in the nation which is 2.5 times greater than the current consumption. This study also found that logging and other residues, fuel treatments, and fuelwood can alone contribute about 47% of total estimated biomass available from forestlands and other 53% can come from urban wood residues, wood processing residues, and pulping liquor. Similarly, Walsh et al. (2000) found that at a market price below $30/dry ton delivered, the total amount of forestry feedstocks available (excluding wood obtained from urban areas but including forest mill residues, dedicated forestry crops, and forestry residues) would account for approximately 24% of all cellulosic biomass available in the nation. However, the amount of available forestry feedstocks would increase to 45% of the total cellulosic feedstocks available at a market price up to $40/dry ton delivered. These studies clearly show that forest biomass can play a significant role in meeting the overall feedstock demand for bioenergy development in general and cellulosic ethanol in particular.

Southern Forestlands and Bioenergy Development

The total forest area of the United States is about 747 million acres out of which 28% (214 million acres) is located in the southern region (Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, Missouri, North Carolina, Oklahoma, South Carolina, Tennessee, Virginia, and West Virginia). The majority of the region's forestland (210 million acres) is classified as timberlands as their annual average productivity is greater than 20 ft^3/acre/yr. Non-Industrial Private Forest (NIPF) landowners own 151 million acres of forestlands or 143 million acres of timberlands in the region and are major suppliers of roundwood products at the national level (Smith 2001). For example, NIPF landowners supplied 60% of total roundwood production in the country (9.5 billion cubic feet) in 1997 out of which 67% was sourced from southern NIPF lands (6.67 billion cubic feet). This implies that southern NIPF landowners alone supplied about 42% of the total roundwood production at the national level (Smith 2001). This clearly highlights the importance of southern NIPF landowners in meeting the future demand for bioenergy development at the national level.

Inspired by the prospectus, various state governments in the southern region have created special policy instruments to promote forest biomass-based bioenergy development in their states. For example, three agencies in the state of Georgia (Georgia Environmental Facilities Authority, Georgia Forestry Commission, and Georgia Department of Economic Development) have been grouped under the umbrella of Georgia's Bioenergy Partnership to promote forest biomass-based bioenergy development. Similarly, in the state of Florida several grants have been announced by the Florida Energy & Climate Commission to promote biofuel production from cellulosic feedstocks available within the state.

However, utilization of forest biomass for bioenergy development also raises concerns. For example, it is expected that the bioenergy markets could intensify the current regimes of forest management leading to adverse consequences for biodiversity and soil-moisture conservation (Spangenberg 2008). There are also concerns about the absence of viable commercial technologies for biomass conversion to various energy products (Phillips et al. 2007). Similarly, people are concerned about the absence of a supportive policy in the region that could incorporate the aspirations of various stakeholders about the use of forest biomass-based bioenergy development in the region.

Problem Statement

Forest biomass available in the Southern United States will play an important role in meeting the future demand for ethanol in the country. Therefore, it becomes imperative to assess the environmental and economic sustainability of forest biomass-based ethanol production in the region. Currently, very limited information exists. Similarly, it is expected that emerging bioenergy markets will affect the profitability of NIPF landowners. The situation becomes more complex due to emergence of another market which provides monetary incentives to NIPF landowners for carbon sequestered on their forestlands. So far, how these two markets will affect the supplies of forest biomass and the profitability of an NIPF landowner is not well understood. Additionally, perceptions of various stakeholders about forest biomass-based bioenergy markets which are critical for policy and/or program development are not systematically assessed. Therefore, there exists a need for a study that could fill critical existing gap in our understanding and can aid in suitable policy formation in the future.

Research Significance and Objectives

This study aims to address some of the fundamental questions related to the production of cellulosic ethanol from forest biomass obtained from southern NIPF lands. These questions include the following:

a) What is the present status of various conversion technologies which are used to produce cellulosic ethanol?

b) What is the energetic content and global warming impact of cellulosic ethanol produced from forest biomass available from NIPF lands in the Southern United States?

c) How will emerging voluntary carbon and bioenergy markets affect the profitability of an NIPF landowner in the Southern United States?

d) What are the perceptions of stakeholders about the forest biomass-based bioenergy development in the Southern United States?

In order to address the first research question, a comprehensive literature review was done and the status of existing conversion technologies was assessed. The process, production cost of ethanol, and adoption rates were recorded for each technology. Emerging conversion technologies were also discussed. For the second research question, a detailed life-cycle assessment was undertaken by accounting for all the inputs and emissions from the seed orchard to the point where E85[4] is used as a fuel in an automobile. An attempt was also made to estimate the unit cost of ethanol production. For the third question, guidelines of Chicago Climate Exchange for Managed Forest Projects were followed to simulate voluntary carbon markets. A detailed carbon model was used to monitor changes in the soil carbon. A benefit-cost analysis and a life-cycle assessment were integrated to assess the effects of carbon and bioenergy markets on an NIPF landowner profitability. Finally, a SWOT-AHP

[4] A mixture of 85% ethanol and 15% gasoline by volume.

(Strength, Weakness, Opportunity, Threats—Analytical Hierarchy Process) approach was applied to assess stakeholders' perceptions with respect to forest biomass based bioenergy markets.

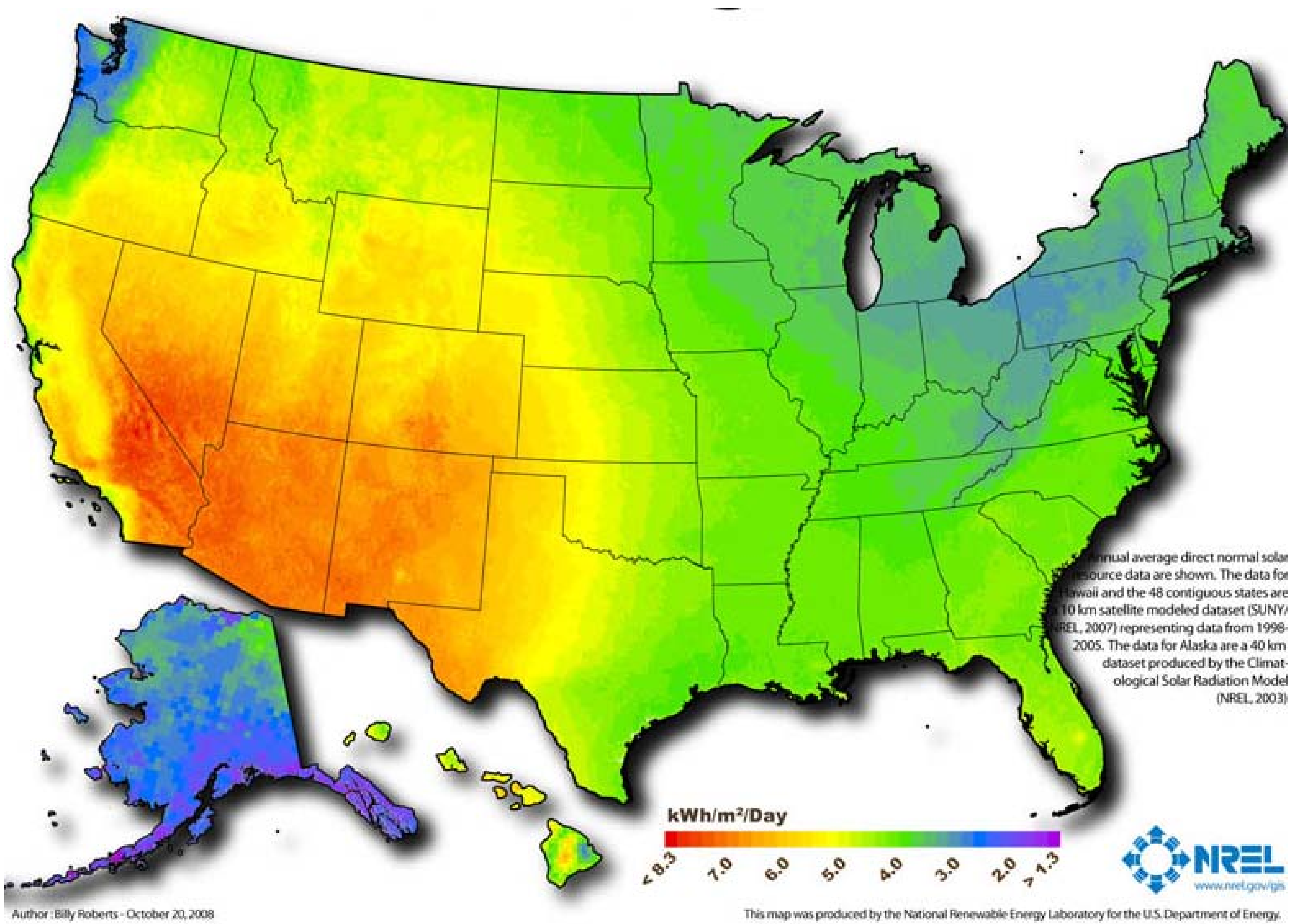

Figure 1-1. Solar resources of the United States

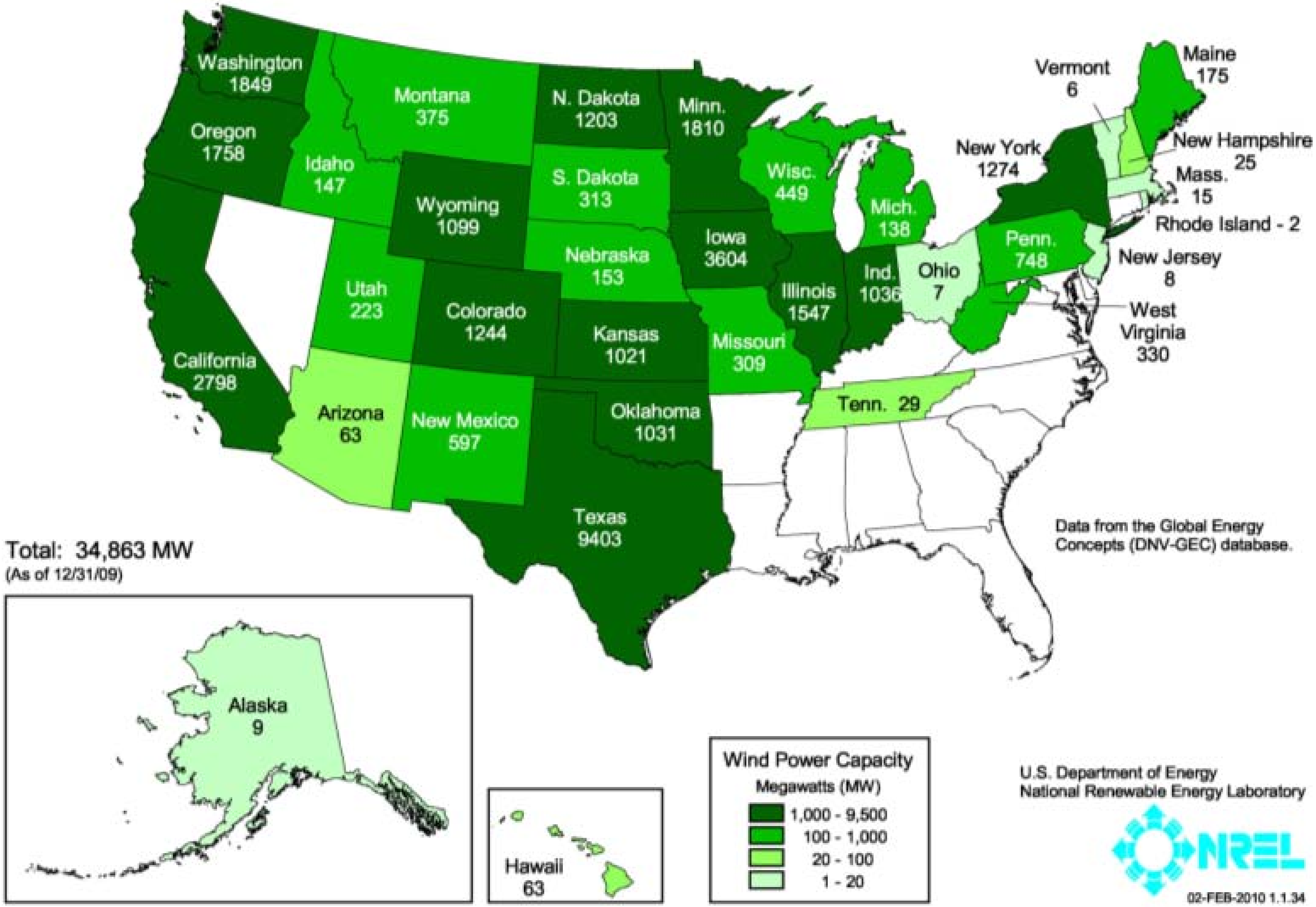

Figure 1-2. Wind-based power production in the United States until yearend 2008

CHAPTER 2

CELLULOSIC ETHANOL PRODUCTION IN THE UNITED STATES: CONVERSION TECHNOLOGIES, ECONOMICS, AND FUTURE DEVELOPMENTS

Introduction

Because of rising energy dependency, increasing emission of greenhouse gases, and risks associated with price fluctuations in the international energy market, federal and various state governments have started to develop new energy strategies which emphasize on the development of various renewable energy sources. Out of many renewable energy resources (biomass, solar, wind, geothermal, tidal, etc.), biomass is given a high priority as it is the only source which can be directly utilized for the production of various alternative transportation fuels especially ethanol. Using food crops for ethanol production raises concerns of food security (Mitchell 2008) and environmental degradation (Pimentel and Patzek 2005); therefore majority of petroleum importing countries (e.g., United States) are interested in utilizing cellulosic biomass as a feedstock for ethanol production.

As the United States has a large cellulosic biomass production base (Perlack et al. 2005), therefore production of ethanol from cellulosic feedstock and utilizing it as a substitute for gasoline could help in promoting rural development, reducing greenhouse gas emissions, and achieving energy independence. Inspired by the potential benefits of utilizing cellulosic biomass for ethanol production, the federal government has announced various policy targets and incentives to promote cellulosic ethanol production in the country. For instance, the Energy Independence and Security Act of 2007 aims to produce about 21 billion gallons of biofuels from cellulosic feedstocks by 2022. Additionally, the recently enacted the Food, Conservation, and Energy Act of 2008 provides a subsidy of $1.01 on every gallon of produced cellulosic ethanol.

Several technologies have been developed to convert different cellulosic feedstocks into ethanol. These technologies range from fermentation (Lin and Tanaka 2006) to gasification (Perkins et al. 2008). However, the commercial viability of existing conversion technologies is doubtful (Waltz 2008; Tan et al. 2008; Ruan et al. 2008; Wright and Brown 2007). As a result, the federal and various state governments are providing funding support to several private companies and public institutions to develop a suitable conversion technology through which cost of ethanol production from various cellulosic feedstocks can become comparable to the cost of ethanol produced from different agricultural feedstocks. Already, federal government has provided a funding support of about a billion dollars to develop a commercial viable conversion technology for cellulosic ethanol production (Curtis 2008). It is expected that the successful demonstration of at least one conversion technology on a commercial scale will help in increasing the confidence of investors in cellulosic ethanol production and, thus, in achieving the policy target.

In light of the importance given to the development of a commercially viable conversion technology, it is essential to review the status of existing conversion technologies to ascertain their performance in terms of adoption status and economics. Such an attempt will help in creating a baseline for the emerging conversion technologies and in guiding policy makers to streamline funding and institutional support. Therefore, the present study is an attempt to summarize details of existing conversion technologies for cellulosic ethanol production and to evaluate their performance in terms of unit cost of ethanol produced and adoption status. Recent developments are also identified to facilitate future technology development.

In the next section, the composition of cellulosic feedstock is briefly discussed. In the third section, two major conversion technologies or base technologies that are commonly used for converting cellulosic feedstocks into ethanol i.e., hydrolysis and thermo-chemical conversion are explained. An attempt is also made to capture the existing versions of both base technologies. In the fourth section, the adoption status of existing conversion technologies is discussed. In the fifth section, economics of existing conversion technologies in terms of unit cost of produced ethanol is discussed. In the sixth section, emerging trends in the technology development and alternate uses of cellulosic biomass are discussed, and finally the study is concluded in the seventh section.

Cellulosic Feedstock Composition

Cellulosic feedstock is composed of cellulose, hemicellulose, lignin, and solvent extractives. Lignin acts as a cementing material and binds all other constituents together. It is also responsible for providing structural rigidity to a cellulosic feedstock. Cellulose is a polymer of repeating β-D-glucopyranose units and is a chief constituent of the feedstock. Hemicellulose like cellulose is a polysaccharide but is less complex and easily hydrolysable. Soluble materials or extractives in the feedstock consist of those components that are soluble in neutral organic solvents. The distribution range of different constituents in softwood and hardwood is reported in Table 2-1 (Anonymous 2008; Miller 1999).

Sugar present in the cellulose is mostly glucose. However, hemicellulose is a mixture of different types of sugars. It contains both C6 (glucose, mannose, and galactose) and C5 (xylose, arabinose, and rhamnose) sugars. Glucose, mannose, and xylose constitute about 95-97% of the total sugars. For example, distribution of sugars in loblolly pine (*Pinus taeda*), a commercial pine species of the Southern United States, is shown in Table 2-2 (Frederick et al. 2008a).

Base Technologies

At present, several technologies are in use for converting cellulosic feedstocks into ethanol. They can be grouped into two broad categories—hydrolysis and thermo-chemical conversion. In hydrolysis-based technologies, the polysaccharides (cellulose and hemicellulose) present in a feedstock are broken down to free sugar molecules (glucose, mannose, galactose, xylose, and arabinose). This process is also known as saccharification. These free sugar molecules are then fermented to produce ethanol. As lignin cannot be used for ethanol production, it is removed during the conversion process and is generally utilized for meeting electricity or heat requirement of an ethanol mill.[1] In thermo-chemical based technologies, the feedstock is gasified to produce syngas (a mixture of carbon monoxide, hydrogen, carbon dioxide, methane, and nitrogen) which is either fermented or catalytically converted to obtain ethanol.[2] Production of ethanol through thermo-chemical route is independent of the sugar quantities originally present in the feedstock.

Details of specific technologies under each broad category of conversion technology i.e., hydrolysis and thermo-chemical conversion are discussed below.

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[1] Technologies which hydrolyze the sugars to produce ethanol are also known as sugar platform technologies.

[2] Gasification is a process that uses heat, pressure, and steam to convert different materials including cellulosic biomass into syngas composed primarily of carbon monoxide and hydrogen (Rezaiyan and Cheremisinoff 2005).

Hydrolysis Technology

Hemicellulose and lignin present in the feedstock provide a protective covering to the cellulose. This protective cover should be altered for ensuring efficient hydrolysis. Therefore, special provisions are needed to loosen the feedstock structure completely before undertaking cellulose hydrolysis. Figure 2-1 explains basic steps generally undertaken while converting cellulosic feedstocks to ethanol through hydrolysis.

During feedstock preparation, feedstock is first washed to remove dust and any other impurities. Then, it is chipped or milled to increase the surface area so that chemicals/enzymes used in the subsequent steps can easily penetrate the feedstock structure. In the pretreatment process (also called first stage hydrolysis),[3] hemicellulose is hydrolyzed into the basic sugars (xylose, mannose, arabinose, and galactose). A small amount of cellulose is also hydrolyzed to glucose during the pretreatment. The mixture obtained at the pretreatment is separated into liquid and solid (lignin + unhydrolyzed cellulose). The liquid is filtered and sent to a fermentation column for ethanol production. Solids are sent for another round of hydrolysis (also called second stage hydrolysis). Again, at the end of the hydrolysis the mixture is separated into liquid and solid (lignin). After filtration, liquid is sent to a fermentation column for ethanol production and lignin is fed into a boiler for heat production. Different types of microbes are needed for fermenting sugars obtained from cellulose and hemicellulose and converting it to ethanol. After fermentation is over, the mixture of ethanol and water is distilled to separate ethanol. Ethanol is then dehydrated to produce fuel grade ethanol

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[3] Pretreatment also helps in loosening the wood structure completely. As a result, cellulose present in the wood becomes available for hydrolysis in subsequent step.

(<1% of water). Water produced as a part of distillation is diverted towards a wastewater treatment facility. The ethanol obtained is then transported for subsequent use.

Currently, several versions of hydrolysis technology exist though the basic framework remains the same. Each version is distinguished from another depending upon the type of inputs used for hydrolyzing hemicellulose and cellulose into basic sugars. First, different techniques used for feedstock pretreatment (first stage of hydrolysis) are discussed followed by techniques which are commonly used for second stage of hydrolysis.

Pretreatment methods (first stage hydrolysis)

Thermal pretreatment: In thermal pretreatment, feedstock is heated to about 302-356°F to break down the hemicellulose and lignin. At higher temperatures (above 482°F), phenolic compounds are formed which later retard the fermentation process so care is taken not to pretreat the feedstock in severe thermal conditions (Ramos 2003). Four processes are commonly used for accomplishing thermal pretreatment i.e., steam pretreatment/steam explosion, liquid hot water, ammonia fiber explosion, and carbon dioxide explosion. During steam pretreatment, the feedstock is put in a large vessel and then steamed up to a high temperature (464°F) and pressurized for few minutes. After a set time, the steam is released and the biomass is quickly cooled down. The difference between steam and steam explosion pretreatment is the quick depressurization and cooling down of the biomass at the end of the steam explosion pretreatment which causes the water in the biomass to explode (Hendriks and Zeeman 2009; Jeoh 1998). In liquid hot water pretreatment, hot water is added to the feedstock in a slightly acidic environment to solubilize hemicellulose and to prevent formation of any inhibitory compounds (Yang and Wyman 2004). In ammonia fiber explosion, processed feedstock is exposed to liquid ammonia at high temperature/pressure for a small time and then the pressure is swiftly reduced. In a typical procedure, the dosage of liquid ammonia is 2.2-4.5 pounds ammonia per pound of dry biomass, temperature is 194°F, and residence time is about 30 minutes (Sun and Cheng 2002). Similar to steam and ammonia explosion pretreatment, carbon dioxide explosion is also used for pretreatment of processed feedstock. Zheng et al. (1998) reported that the carbon dioxide explosion is more cost effective than ammonia explosion and prevents the formation of inhibitory compounds.

Acid pretreatment: In acid pretreatment, dilute sulfuric acid is added to the feedstock to hydrolyze hemicellulose (0.5-1.5%, temperature is greater than 320°F). Sometimes, concentrated sulfuric acid is also utilized for feedstock pretreatment. The acid must be removed or neutralized before fermentation. Generally lime is used for neutralizing the medium and therefore gypsum is produced as a byproduct of the reaction. Dilute acid pretreatment is the most preferred method for feedstock pretreatment. Recently, nitric acid has also shown positive results in terms of better yields and solubility of lignin (Xiao and Clarkson 1997).

Alkaline pretreatment: Alkaline pretreatment use bases like sodium hydroxide or calcium hydroxide. All lignin and a part of the hemicellulose are removed and the reactivity of cellulose for later hydrolysis is sufficiently increased. Alkaline-based methods are generally more effective at solubilizing a greater fraction of lignin while leaving behind much of the hemicellulose in an insoluble polymeric form (Hamelinck et al. 2005; Mosier et al. 2005).

Oxidative pretreatment: In oxidative pretreatment, oxidative like peracetic acid or hydrogen peroxide is used over the feedstock suspended in the water (Gould 1984). Teixeira et al. (1999) reported that the use of peracetic acid at the ambient temperature increased the ethanol yields by about 98%.

Organosolve pretreatment: In the organosolve process, an organic or aqueous organic solvent mixture with inorganic acid catalysts (hydrochloric acid or sulfuric acid) is used to break the internal lignin and hemicellulose bonds (Sun and Cheng 2002). The organic solvents used in the process include methanol, ethanol, acetone, ethylene, glycol, triehylene glycol, and tetrahydrofurfuryl alcohol (Chum et al. 1988; Thring et al. 1990).

Biological pretreatment: Brown-, white-, and soft-rot fungi are normally used for degrading lignin and hemicellulose present in the feedstock. Recently, Lee et al. (2007) have evaluated the pretreatment effects of three white rot fungi (*Ceriporia lacerata*, *Stereum hirsutum*, and *Polyporus brumalis*) on the Japanese red pine (*Pinus densiflora*). Similarly, Zhang et al. (2007) reported that the biological pretreatment with white rot fungi has a potential for improving enzymatic hydrolysis of wood and grass. They found that fermentable sugar yield of bamboo culms (*Phyllostachys pubescence*) pretreated with two fungi (*Echinodontium taxodii* 2538 and *Trametes versicolor* G20) increased with increasing pretreatment time.

Hydrolysis technologies (second stage hydrolysis)

Acid hydrolysis: Acid hydrolysis is only applicable when feedstock has been pretreated using dilute acid process. Both dilute and concentrated acid options are available for hydrolyzing pretreated feedstock. At this stage, higher temperature (about 419°F) and dilute acid (4%) are used for converting cellulose to glucose. The concentrated acid process has a very high sugar yield (90%), can handle diverse feedstock, is relatively rapid (10-12 hours in total), and causes small degradation of sugars. However, the equipment required is more expensive when compared to dilute acid hydrolysis (Hamelinck et al. 2005).

Enzymatic hydrolysis: Enzymatic hydrolysis provides many advantages over acid hydrolysis. For example, enzymatic hydrolysis takes place at mild conditions of temperature and pressure. As a result glucose yields are high, chances of fermentation inhibiting compounds are less, equipment requirements are not significant, and there is a reduction in the total environmental impact of the whole process. Cellulases[4] are usually a mixture of several enzymes. At least three major groups of cellulases are involved in the hydrolysis process: a) endoglucanase (EG, endo-1,4-D-glucanohydrolase, or EC 3.2.1.4) which attacks regions of low crystallinity in the cellulose fiber, creating free chain-ends; b) exoglucanase or cellobiohydrolase (CBH, 1,4-β-D-glucan cellobiohydrolase, or EC 3.2.1.91.) which degrades the molecule further by removing cellobiose units from the free chain- ends; c) β-glucosidase (EC 3.2.1.21) which hydrolyzes cellobioase to produce glucose (Coughlan and Ljungdahl 1988; Sun and Cheng 2002).

Fermentation

During fermentation, both C5 and C6 sugars are fermented to ethanol under anaerobic/aerobic conditions. Historically, yeast (*Saccharomyces cerevisiae*) and other microbes like *Zymomonas mobilis* have been used to ferment C6 sugars i.e., glucose.

[4] Cellulase refers to a class of enzymes produced chiefly by fungi, bacteria, and protozoans that catalyze the hydrolysis of cellulose.

Other engineered microbes like *Escherichhia coli* have also been developed to ferment both C6 and C5 sugars.

Based on different combinations of technologies adopted at the pretreatment, hydrolysis, and fermentation stages of ethanol synthesis, several integrated technologies have been developed. In the section below, existing integrated conversion technologies are discussed.

Integrated technologies based on hydrolysis

Simultaneous saccharification and fermentation: In simultaneous saccharification and fermentation, the feedstock is pretreated by dilute acid (1.1% sulfuric acid at 320°F for 10 minutes) to hydrolyze hemicellulose into sugars. The liquor is vented from the system and then neutralized using lime. Then, liquor containing C5 sugars is sent for fermentation. Residual solids comprise of cellulose and lignin. Yeast and enzymes are subsequently added to the residual solids where the enzymes digest cellulose and produce glucose. Yeast and other microbes ferment glucose to produce ethanol separately (Krishna et al. 2001).

Simultaneous saccharification and co-fermentation: In simultaneous saccharification and co-fermentation, the pretreated feedstock is exposed to different enzymes/microbes which not only hydrolyze cellulose and hemicelluloses into different sugars but also ferment sugars into ethanol. This technology is better than the simultaneous saccharification and fermentation technology in terms of cost effectiveness, better yields, and shorter processing time (Wright 1988; Chandel et al. 2007).

Two stage dilute sulfuric acid hydrolysis: Kadam (2000) has described the details of two-stage dilute sulfuric acid hydrolysis. In this process, dilute sulfuric acid is used at pretreatment phase to hydrolyze hemicellulose. In the hydrolysis stage of the process, concentrated sulfuric acid is utilized for hydrolyzing cellulose. After both the stages, the liquid is separated, filtered and then neutralized (using lime) before it is sent for fermentation. Fermentation is conducted in steps. First, glucose is fermented to ethanol by the yeast (*Sacromyces cerevisiae*). The mixture is then distilled to remove the unconverted xylose. Then second yeast (*Pachysolen tannophilu*) is added to the remaining solution to ferment xylose to ethanol. Ethanol produced from xylose is then distilled (Shleser 1994).

Biomass fractionation: In biomass fractionation, feedstock is pretreated using the steam explosion method. The resulting mass is washed by either water or alkali to separate out the components of the biomass i.e., hemicellulose, cellulose, and lignin (Glasser and Wright 1998). Once separated, components containing sugars are further hydrolyzed to produce sugars. Sugars thus produced are fermented to obtain ethanol.

Thermo-chemical Conversion Technology

In thermo-chemical conversion, constituents of feedstock are first converted into syngas under intense heat and partial supply of air inside a gasifier. The produced syngas is then either fermented or catalytically converted to ethanol. Figure 2-2 shows the schematic diagram of ethanol formation through thermo-chemical route. Details of both the technologies i.e., fermentation-based and catalyst-based are discussed below.

Fermentation-based ethanol production

The feedstock is washed to remove any impurities and then chipped to the required size. Chips are dried to attain a desired moisture level (5-20% by weight). Sand bed present inside a fluidized bed gasifier is preheated to a temperature of about 1,022°F using an external fuel supply. Once optimum temperature is achieved, the feedstock is fed into the bed. On coming in contact with the hot sand, the feedstock decomposes producing syngas. The supply of air is simultaneously controlled to prevent complete combustion of feedstock and to raise the temperature of the sand bed to approximately 1,472°F. Once the optimum conditions are achieved, the gasifier can run on its own without any external supply of additional fuel. The syngas so produced is collected from the top of the gasifier. Gas is cleaned to remove tar and ash. Once cleaned, gas is cooled to the normal ambient temperature and stored at a high pressure. Cooled and cleaned gas is fed into an ethanol conversion chamber where microbes ferment the gas into ethanol and acetic acid. After fermentation is complete, the liquid is distilled to separate ethanol from other products. The ethanol produced is then dehydrated to produce fuel quality ethanol. Many microbes have been developed which can successfully ferment the syngas into required compounds like *Clostridium carboxidivorans* P7 (Liou et al. 2005), *Clostridium ljungdahlii*, and *Clostridium autoethanogenum* (Abrini et al. 1994; Vega et al. 1990). Rajagopalan et al. (2002) reported that the fermentation of syngas by the microbe (P7) is sensitive to the syngas constituents and proper cleaning of syngas ensures effectiveness of the process. For example, Ahmed et al. (2006) reported that presence of nitric oxide in the syngas (150 ppm) prevents fermentation of gas constituents by the P7.

Catalyst-based ethanol production

In catalyst-based ethanol production, all the processes remain the same until the gas enters into an ethanol conversion chamber. Before entering the chamber, gas is heated to 572°F at a pressure of 69 bar. Gas is also mixed with water and methanol to improve yield of higher alcohols. The mixture is passed through the synthetic catalyst (molybdenum-disulfide based) to obtain methanol, ethanol, and higher linear alcohols up to pentanol, water, methane, and minor amounts of other hydrocarbon byproducts. The chamber effluent is finally cooled to 109.4°F using cooling water, and excess syngas is diverted to the gas cleaning area. The effluent so obtained is sent to distillation for ethanol recovery. Finally, the ethanol obtained is dehydrated to make it suitable for vehicles (Phillips 2007).

Current Production Status of Cellulosic Ethanol Production

Encouraged by the subsidies offered by federal government, many private entrepreneurs have ventured into cellulosic ethanol production. Figure 2-3 shows the details of the total quantities of cellulosic ethanol currently or expected to be produced within the country by employing different conversion technologies (RFA 2009).

As observed from Figure 2-3, it is expected that about 405 million gallons of cellulosic ethanol will be produced by the end of 2012 and three conversion technologies (enzymatic hydrolysis; simultaneous saccharification and fermentation; and gasification catalytic conversion and distillation) will dominate the total production. Government has so far supported existing cellulosic ethanol producers through various grants. It is presumed that the commercial viability of cellulosic ethanol production will be proven to private investors by the end of 2012 (Sandor et al. 2008) and thereafter, the cellulosic ethanol production will shoot up. In addition to commercial cellulosic ethanol units, many small scale cellulosic ethanol mills are coming up at various places to test the efficacy of newly developed conversion technologies or feedstocks. For example, CitrusEnergy, LLC is planning to use citrus waste to produce ethanol in Florida (CitrusEnergy 2009).

It was observed that the majority of cellulosic ethanol mills which are under construction have plans to meet their cellulosic feedstock supply either from the agriculture sector (corn stover, corn cob, wheat straw, rice straw, barley straw, switch grass, sugar cane) or from municipal solid wastes. Based on the current trend, it is expected that there will be only handful of cellulosic ethanol mills which will utilize forest biomass as feedstock in the future.

Economics of Cellulosic Ethanol Production

Production of ethanol from cellulosic feedstocks is costly when compared to its production from starch-based agricultural feedstocks (McAloon et al. 2000). Therefore the goal of the several research agencies is to bring down the cost of production of cellulosic ethanol to $1.33/gal or below by the end of 2012 by improving overall efficiency of conversion technologies (EERE 2009b). Several authors have attempted to estimate cost of cellulosic ethanol produced through different conversion technologies. Few such studies are discussed below.

Hydrolysis-based Technologies

Shleser (1994) compared the cost of ethanol produced using seven integrated hydrolysis-based conversion technologies. Results of their study are summarized in Table 2-3. It becomes clear from Table 2-3 that the production cost of ethanol falls as the scale of the ethanol mill increases. Also, the total production cost of the ethanol is directly related to the cost of biomass feedstock. It was found that among all the hydrolysis-based conversion technologies, the production cost of ethanol was highest for the concentrated acid hydrolysis, neutralization, and fermentation technology and lowest for simultaneous saccharification and fermentation technology. Recently, Huang et al. (2009) stated that for an ethanol mill based on simultaneous saccharification and co-fermentation technology, the ethanol production cost decreases with increasing plant sizes in the range of 1,100 dry tons/day to 4,400 dry tons/day. It was also found that the production cost of ethanol from hybrid poplar increases if the plant size is more than 4,400 dry tons/day as feedstock costs rise faster than non-feedstock costs. Sassner et al. (2008) have analyzed the cost effectiveness of three cellulosic feedstocks (namely salix, corn stover, and spruce) and concluded that conversion technology used for ethanol production has more important implications for the cost-effectiveness of a conversion process than the type of feedstock used.

So and Brown (1999) found that the production cost of ethanol from a 25 million gallon/year ethanol plant was $1.57/gal for fast pyrolysis integrated with a fermentation step, $1.28/gal for simultaneous saccharification and fermentation, and $1.35/gal for dilute sulfuric acid hydrolysis and fermentation conversion technologies. Wooley et al. (1999) have found that to minimize the production cost of ethanol produced using corn stover as a feedstock and co-current dilute acid prehydrolysis and enzymatic hydrolysis as a technology emphasis should be on increasing the conversion efficiencies of hemicelluloses and cellulose to fermentable sugars. Hamelinck et al. (2005) echoed similar thoughts. They analyzed four technologies and three scenarios and found that commercial production of cellulosic ethanol was feasible with an increase in sugar conversion efficiencies. Aden et al. (2002) also found that the total cost of ethanol production almost becomes flat i.e., $1.3/gal when plant size crosses a threshold value of about 6,600 metric tons of corn stover/day. They used co-current dilute acid prehydrolysis with simultaneous saccharification (enzymatic) and co-fermentation conversion technology for their analysis.

Recently, Aden (2008) for a 55 million gallons/year ethanol production facility found that the total selling price of ethanol is about $2.43/gallon when simultaneous saccharification and co-fermentation technique is used for ethanol production. It was also noted that the selling price has shown continuous declining trends since 2001. Feedstock costs were found to be about 40% of the total selling price of ethanol. Leistritz et al. (2006) analyzed the production cost of ethanol (using enzymatic hydrolysis conversion technology) from wheat straw in North Dakota and estimated the production cost of produced ethanol to be $1.56/gal. Feedstock costs have been found to be significant in determining the final cost of the ethanol especially when the conversion technology costs are falling at a faster pace (Bohlmann 2006).

Thermo-chemical Technologies

There is no commercial scale plant using thermo-chemical conversion, so production costs can only be estimated. Phillips (2007) modeled cellulosic ethanol production through gasification technology and catalytic conversion of syngas to ethanol. The minimum selling price was found to be $1.07/gal based on the anticipated and achievable technology parameters by 2012. Tembo et al. (2003) noted that the breakeven cost for the ethanol produced using thermo-chemical-fermentation technology will be about $0.76/gal. Recently, Piccolo and Bezzo (2009) have estimated that the production cost of ethanol produced using gasification-fermentation based technology will be higher than that of the enzymatic hydrolysis technology. Wei et al. (2009) have found that the cost of ethanol produced using gasification-catalytic conversion technology will be lower than the cost of ethanol produced using hydrolysis fermentation as processing time is lowest in the former technology.

The literature review on unit production cost of ethanol clearly reveals that the unit cost of ethanol production has fallen in recent years due to technological advancements and it is expected that the cost of producing ethanol from cellulosic feedstocks will soon become comparable to the starch-based ethanol. It was also observed that the scale of operations has an impact on the production cost of ethanol and optimum size of an ethanol mill should be close to 4,400 dry tons/day of feedstock consumption. Furthermore, the type of feedstock does not appear to be significant in determining the production cost of ethanol compared to the conversion technology. It can be inferred that the future production cost of ethanol will be lowest for gasification-catalytic conversion followed by hydrolysis and then the gasification-fermentation technology. There also exists a need for reducing the cost of transporting feedstocks to the ethanol mill, as feedstock costs constitute significant portion of the total production cost of ethanol.

Emerging Developments

The importance given to the commercial viability of ethanol production from cellulosic feedstocks has attracted many scholars. Several new techniques for ensuring commercial production of ethanol from cellulosic feedstocks are being tried at various levels. Some of these emerging technologies are discussed below.

Consolidated bioprocessing: In consolidated bioprocessing only one microbial community is employed both for the production of cellulases and fermentation i.e., cellulose production, cellulose hydrolysis, and fermentation are carried out in a single step (Cardona and Sánchez 2007). Lynd et al. (2005) estimated that consolidated bioprocessing has a potential to provide the lowest cost route for biological conversion of cellulosic biomass to fuels and other products among all the hydrolysis-based processes.

Mobile fast pyrolysis: Reducing transportation costs will help in ensuring cost-effective production of cellulosic ethanol because cellulosic biomass is a light density solid and therefore it occupies a large volume resulting in increased transportation costs. One way to overcome this problem is to densify the feedstock at the harvest site and then transport it to the mill site (Li and Liu 2000; Petrolia 2008; Husain et al. 2002). Recently, establishment of mobile fast pyrolysis plants at the feedstock source for producing pyrolysis oil has been suggested as a potential solution (Badger and Fransham 2006). It was observed that the energy density of pyrolysis oil is about 6-7 times higher than the energy density of green whole tree chips at 45% and 56% moisture content, respectively (Czernik and Bridgwater 2004). Pyrolysis oil can be gasified and syngas can be utilized for ethanol production. However, pyrolysis oil is very complex and unstable and therefore, there exists a need of advanced research to successfully utilize pyrolysis oil for ethanol production.

Integrated ethanol refineries: Increasing energy efficiency of the whole conversion process is the key towards ensuring the commercial viability of cellulosic ethanol production. Recently, Frederick et al. (2008b) took a holistic approach and analyzed the whole system of producing ethanol from loblolly pine and using the residual biomass as a fuel for a combined heat and power plant. They found that ethanol can be produced at $1.29/gal based on a delivered wood cost of $58/dry tons at 95% conversion efficiency of carbohydrates in wood to sugars for a 93 million gallons annual plant capacity. Frederick et al. (2008a) also analyzed the feasibility of ethanol production in a Kraft Paper mill. They found production cost of ethanol to be between $1.33/gal and $2.92/gal depending upon process conditions and selectivity of hemicelluloses removal. Leistritz et al. (2006) have also evaluated the integrated biorefinery concept in North Dakota and found that the production of cellulose nanowhiskers would be an enhancement to the economic performance of a wheat straw to ethanol mill.

Biopower: Cellulose used for ethanol production has to compete with alternative uses. One such use is power production. Biopower plays a major role in total renewable electricity produced in the nation as about 16% electricity produced from renewable sources comes from biomass alone (EIA 2008a). Fuelled by several incentives announced by the government, the interest in using biomass for electricity production has gone up and many entrepreneurs are establishing new cellulosic feedstock based power plants. For example, Gainesville Regional Utilities will establish a 100MW power plant in Gainesville, Florida which will use various cellulosic feedstocks for electricity production (GRU 2009). It is possible that the rise in number of such power plants will increase the competition for available cellulosic biomass and can severely affect the availability of cellulosic biomass for ethanol production.

Conclusions

Production of cellulosic ethanol presents a challenge in terms of development of a commercially viable conversion technology. However, with the rising interest of policy makers and researchers, it is expected that such a technology will soon be developed. It is more likely that the developed conversion technology will be based on the thermo-chemical platform rather than sugar platform as embedded technologies like gasification and catalytic conversion are already quite mature and only small improvements are needed to customize the present technology for ethanol production. Similarly, it is also expected that efforts in reducing the feedstock costs would bring down the total cost of cellulosic ethanol production.

In terms of cellulosic ethanol production using different technologies, so far only three technologies have gained broader acceptance among entrepreneurs. This implies that the industry has accepted only handful of technologies to produce cellulosic ethanol and there exists a need to test more technologies to ascertain their commercial viability. Also, attempt should be made towards exploring the efficacy of ethanol production from other feedstocks like woody biomass. This will not only help in diversifying the feedstock portfolio but also add to the energy security of the nation in case of a crop failure due to some natural calamity like pest attach or storms.

Cellulosic ethanol holds a promise to supplement the growing energy needs of the nation. However, at the same time it is important to strike a harmonious chord with other natural processes that are associated with the production of cellulosic feedstocks. For example, in case of forestry feedstocks, it is important to evaluate the impacts of biomass production on the local biodiversity and on the local watershed. Similarly, in case of agricultural feedstocks, it is important to evaluate the impact on soil and water conservation and nutrient management of soils. Understanding these relationships will help in developing a comprehensive cellulosic feedstock-based bioenergy infrastructure in the country.

Table 2-1. Distribution range of wood components

Wood Components	Hardwood (%)	Softwood (%)
Cellulose	40 - 50	40 – 50
Hemicellulose	25 - 35	25 – 30
Lignin	20 - 25	25 – 35
Pectin	1-2	1-2
Starch	Trace	Trace

Table 2-2. Chemical constituents of loblolly pine (%)

Constituents	Percentage (%)
Cellulose (C6)	43.6
Hemicellulose convertible to sugars	
Mannan (C6)	10.8
Galactan (C6)	2.2
Xylan (C5)	6.6
Arabinan (C5)	1.6
Acetal	1.1
Uronic anhydride	3.7
Lignin	26.8
Extractives	3.2
Ash	0.4
Total	100.0

Table 2-3. Economics of hydrolysis-based conversion technologies

Conversion Technologies	Biomass cost: $50/ton (dry matter)		Biomass cost: $108/ton (dry matter)	
	Ethanol ($/gal) 25 Mgal/yr	Ethanol ($/gal) 5 Mgal/yr	Ethanol ($/gal) 25 Mgal/yr	Ethanol ($/gal) 5 Mgal/yr
Simultaneous saccharification and fermentation	1.48	1.88	2.11	2.51
Concentrated acid hydrolysis, neutralization and fermentation	2.28	2.76	3.01	3.49
Ammonia disruption hydrolysis and fermentation	1.81	2.4	2.48	3.06
Steam disruption, hydrolysis and fermentation	1.63	2.15	2.25	2.77
Acid disruption and transgenic microorganism fermentation	1.86	2.45	2.5	3.1
Concentrated acid hydrolysis, acid recycle and fermentation	1.86	2.19	2.5	2.83
Acidified acetone extraction, hydrolysis and fermentation	1.7	2.13	2.3	2.72

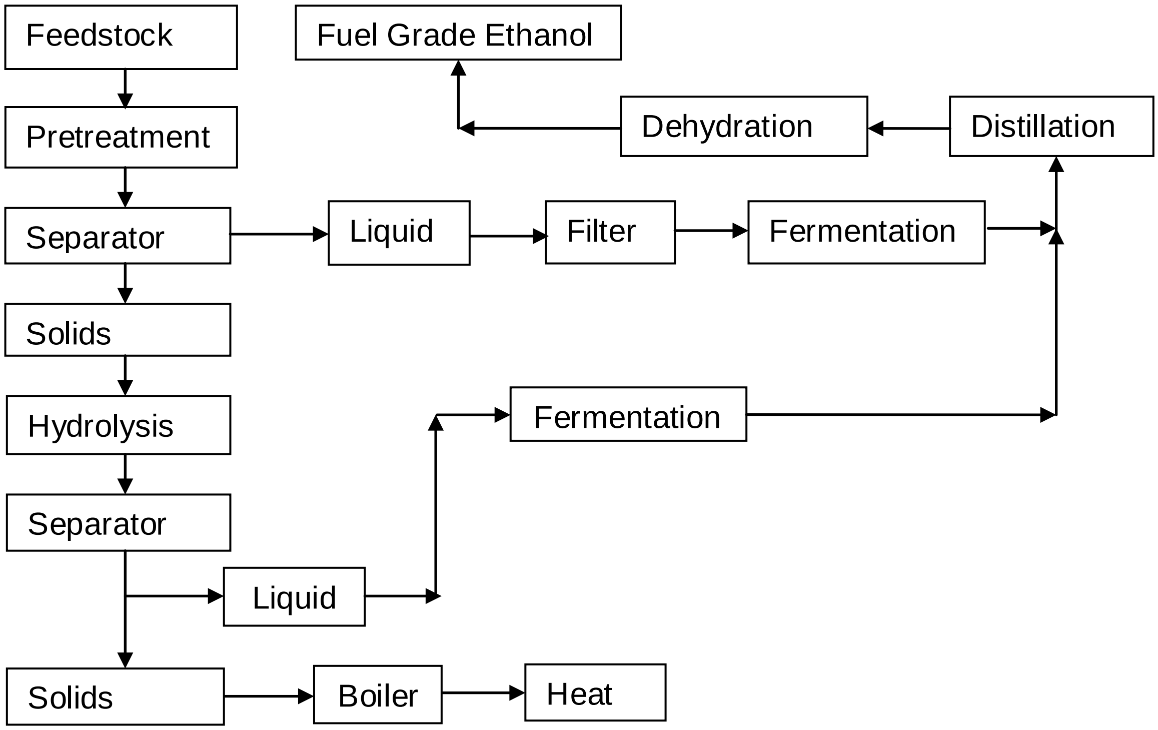

Figure 2-1. Cellulosic ethanol production using hydrolysis-based technologies

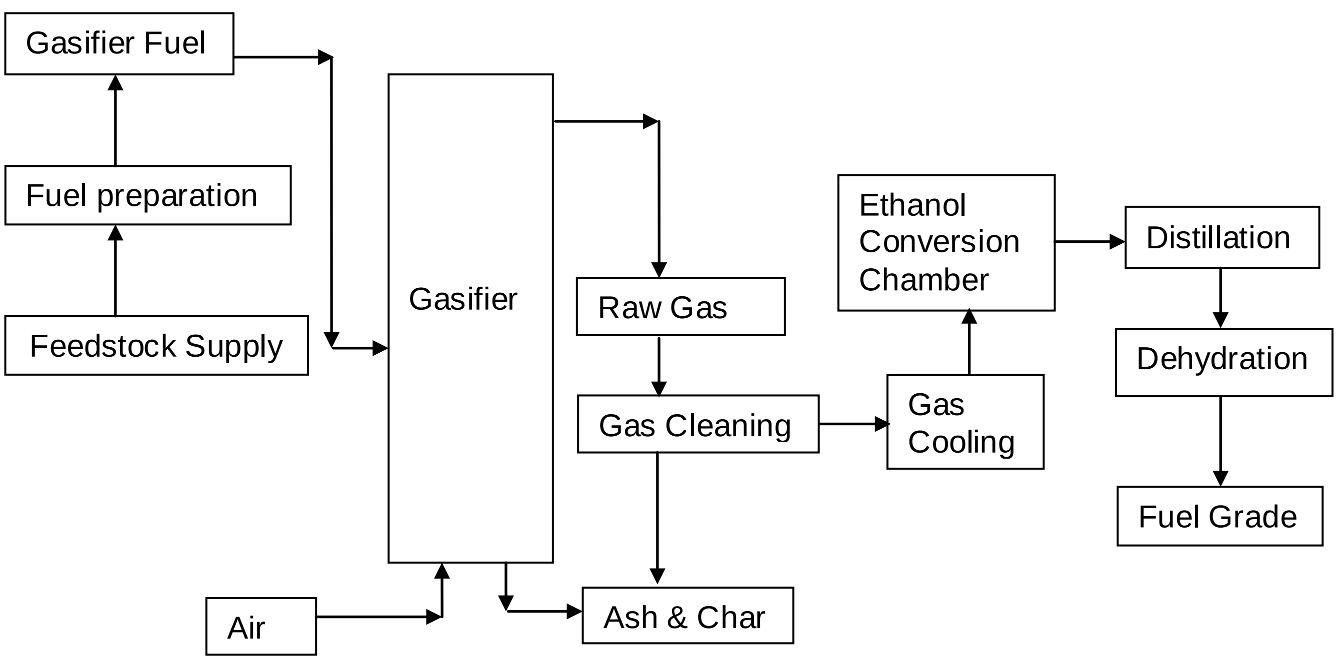

Figure 2-2. Cellulosic ethanol production using gasification technology

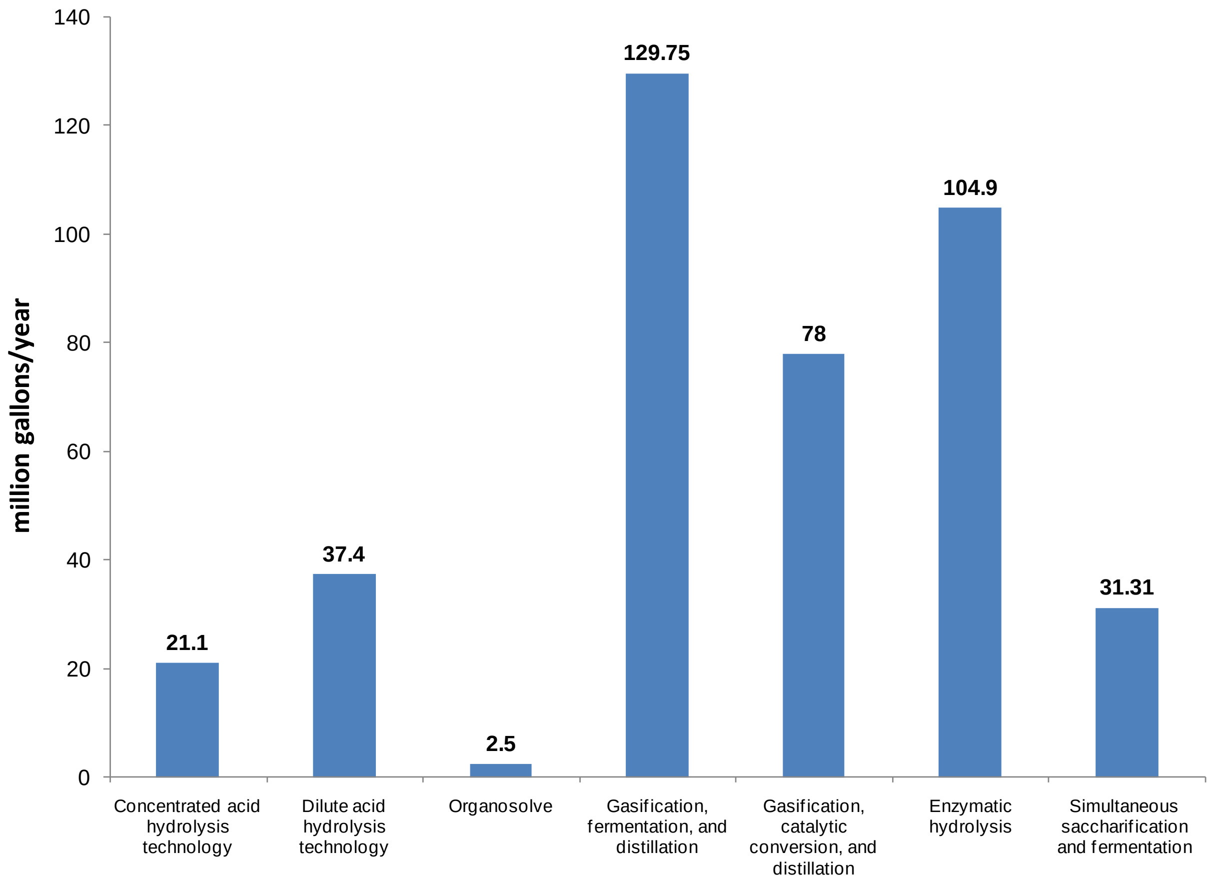

Figure 2-3. Installed and under construction cellulosic ethanol production capacity disaggregated by adopted conversion technologies (RFA 2009)

CHAPTER 3
LIFE-CYCLE ASSESSMENT FOR EVALUATING ENVIRONMENTAL AND ECONOMIC SUSTAINABILITY OF ETHANOL PRODUCTION FROM FOREST BIOMASS

Introduction

Incentives provided by the federal government and various other state governments have supported ethanol production in the United States (Solomon et al. 2007). Therefore, the ethanol production has increased from 175 million gallons in 1980 to about 9 billion gallons in 2009 (RFA 2009). Currently, the majority of ethanol produced within the country comes from corn. Using corn for ethanol production raises concerns of food security (Mitchell 2008). As a result, the government is encouraging production of ethanol from various cellulosic feedstocks. For example, the Energy Independence and Security Act of 2007 aims to produce about 21 billion gallons of cellulosic ethanol by the year 2022. This act also puts a 15 billion gallon cap on ethanol produced from food-based crops. Furthermore, recently enacted the Food, Conservation, and Energy Act of 2008 provides a subsidy of $1.01 on every gallon of cellulosic ethanol produced.

Forest biomass can play a pivotal role in meeting the growing demand of various cellulosic feedstocks for ethanol production in the United States. For example, Walsh et al. (2000) found that at a market price of up to $30/dry ton delivered, the total amount of forestry feedstocks available (excluding wood obtained from urban areas but including forest mill residues, dedicated forestry crops, and forestry residues) would account for approximately 24% of all cellulosic biomass available in the nation. However, the amount of available forestry feedstocks would increase to 45% of the total cellulosic feedstocks available at a market price of up to $40/dry ton delivered.

Southern states (Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, Missouri, North Carolina, Oklahoma, South Carolina, Tennessee, Virginia, and West Virginia) are rich in forest resources. Southern forestlands constitute about 30% (about 214 million acres) of total forestlands present in the country but supply the majority of harvested forest biomass at the national level. For example, the total biomass harvested from southern forestlands was about 9.5 billion cubic feet, which was about 60% of the total biomass obtained from nation's forestlands in the year 1997 (Smith et al. 2001). As Nonindustrial Private Forest (NIPF) landowners own about 70% of the total forestlands in the Southern United States (Smith et al. 2001); therefore, the role of southern forestlands and NIPF landowners in meeting the future demand for cellulosic feedstocks to produce cellulosic ethanol cannot be ignored.

The majority of roundwood production in the southern region is available in four forms—softwood sawlogs (30.03%), softwood pulpwood (26.56%), hardwood pulpwood (14.71%), and hardwood sawlogs (11.09%) (Wear et al. 2007). As noticed, about 40% roundwood harvested in the region is in the form of hardwood and softwood pulpwood and therefore, prices of pulpwood are important in ensuring profitability to NIPF landowners. However, a steep decline in the demand for pulpwood was registered in late 1990s due to imbalance between supply and demand. The reduction in demand and presence of excess supply in late 1990s led to a sharp fall in the market prices of pulpwood. Reduction in softwood and hardwood pulpwood prices has affected investment in forest plantations as evident by a recent decline in the annual planting area (Figure 3-1) (Wear et al. 2007).

Use of forest biomass for cellulosic ethanol production can help NIPF landowners by providing them a new market for their small-diameter wood products like pulpwood and fuelwood (Vogt et al. 2005). This new source of income could improve their financial returns from forestlands. This is especially true when several NIPF landowners (especially who have large land holdings) are interested in financial returns obtained through timber production on their forestlands (Kluender and Walkingstick 2000; Birch 1997). It is expected that the removal of biomass for ethanol production could also provide other ecological benefits as well, such as wildfire prevention, wildlife habitat improvement (Mengak and Guynn 2003), and reduction in pest and disease infestations (Covington et al. 1997).

In order to be a viable energy source, ethanol derived from forest biomass must be environmentally benign and economically competitive relative to the ethanol produced from other feedstocks like corn, corn stover, and switchgrass. Considering the potential of Southern forestlands in meeting the national and regional biomass demand for cellulosic ethanol production, this study adopts a case study approach and assesses the environmental and economic suitability of ethanol production from slash pine (*Pinus elliottii* Engelm.) biomass. Slash pine is a dominant commercial species of the Southern United States and planted by NIPF landowners for financial benefits. The total area of slash pine plantations under private ownership was about 7 million acres in 2005 (USFS 2005) in seven Southern states.

The present study assumes that the biomass for ethanol production will be sourced from an intensively-managed slash pine plantation owned by an NIPF landowner with a rotation age of 25 years. Note that NIPF landowners have considerably augmented intensity of forest plantation management in past few decades especially for pine plantations in the southern region (Siry 2002; Albaugh et al. 2007). Therefore, an assumption of intensive management of slash pine plantation in this study seems logical. It is expected that NIPF landowners will continue to follow the same intensive-management practices in the near future. The rotation age of 25 years was selected assuming that a landowner will be interested in producing large-diameter timber to increase income from their forestland. This age also matches with the normal rotation age of slash pine plantation in the region.

The total ethanol produced from an acre of slash pine biomass available in the form of pulpwood and logging residue[1] only was selected as a functional unit of the analysis. The selected system boundary for the analysis is outlined in Figure 3-2. A life-cycle approach was adopted to assess the Net Energy Ratio (NER) of produced ethanol. Similarly, the total Global Warming Impact (GWI) of produced ethanol was also determined. A benefit-cost analysis was also undertaken to assess the unit cost of cellulosic ethanol produced at the mill. Additionally, NER and GWI of E85 fuel (85% ethanol and 15% gasoline by volume) which can be produced from the ethanol derived from an acre of requisite slash pine biomass was also calculated. The GWI in both the cases was expressed in terms of carbon dioxide equivalent. Furthermore, the total percentage reduction in carbon emission due to the production and consumption of E85 fuel in an automobile was compared with gasoline.

Methods

This section is divided into 14 components. Details of each component are given below.

[1] Diameter at breast height ≥ 4” and to a merchantable diameter 2” outside bark.

Ethanol yield: The conversion technology selected was two stage dilute sulfuric process (Kadam et al. 2000). Kadam (2000) evaluated the material balance of ethanol produced from sugarcane bagasse using the same conservation technology. The material input and output ratios were suitably adjusted for slash pine biomass to determine ethanol yield from a dry ton of slash pine biomass with 15% moisture. Ethanol yield was estimated to be 62 gallons/dry ton of biomass.

Biomass availability: The total biomass available at the time of harvesting i.e., at the 25th year of plantation was found to be about 198 green tons/acre out of which 36% was available in the form of pulpwood (55.84 green tons) and logging residue (15.77 green tons) (Yin et al. 1998). Therefore, it was estimated that 2,892 gallons of ethanol can be produced from an acre of available biomass.

Energy and material use at the mill: Production of 2,892 gallons of ethanol at the mill will require different inputs (dry biomass, lime, water, ammonia, diesel, and sulfuric acid) and will produce multiple outputs (ethanol, gypsum, ash, lignin, carbon dioxide, and methane). The quantities of different inputs required and outputs produced were estimated using adjusted input-output ratios by following Kadam (2000).[2,3] Assuming that 60% of the total water consumed during the production process will be utilized for steam production (WSTB 2008), the amount of total heat required to produce steam was calculated. The remaining 40% of water was assumed to be treated in a wastewater treatment plant. The total electrical energy required to treat wastewater was calculated by multiplying total quantities of treated water with 0.0424 MJ/cubic feet of

[2] Inputs (expressed in kg/kg of dry slash pine biomass): Lime (0.013), Water (3.591), Ammonia (0.025), Diesel (0.004), and Sulfuric acid (0.048).

[3] Outputs(expressed in kg/kg of dry slash pine biomass) : Ethanol (0.19), Gypsum (0.03), Ash (0.07), Ligneous Residue (0.6), Methane (0.02), and CO_2 (1.31 kg).

wastewater (Tchobanoglous et al. 2003). It was assumed that about 0.68 MJ of electrical energy per dry pound of pine biomass will be utilized to convert wood chips into ethanol (Quintero et al. 2008).

As lignin obtained at the end of the conversion process has a high calorific value, therefore it is generally utilized to meet the heat and electricity requirement of the mill. Therefore, total heat (the boiler efficiency was assumed as 40%) and electricity (conversion efficiency was taken as 75%) that can be produced from burning lignin was calculated and was subtracted from the total energy requirement of the mill to estimate mill's net energy use. Total life of the ethanol mill was taken as 15 years and annual capacity of mill was assumed as 50 million gallons. Total construction steel, stainless steel, and concrete used in the ethanol mill were assumed as 1.6, 1.3, and 28 thousand tons, respectively (Hill et al. 2006).[4] Total construction steel required for the production of required amount of ethanol was calculated by using the formula: allocated construction steel = (2,892 gallons of ethanol * total steel used in the ethanol mill)/total production of ethanol in the life time of the mill.[5] Same formula was used for allocating quantities of stainless steel and concrete.

Nursery area estimation: Required number of seedlings at the nursery were estimated by assuming a plantation density of 708 seedlings/acre at the plantation site. Furthermore, it was assumed that 15% seedlings will be lost during transportation. Therefore, it was found that about 833 seedlings will be required for the estimated plantation area. For estimating required nursery area, seed density of 28 seeds/square

[4] An increase of 10% was assumed from the base values, as forest biomass handling requires extra efforts.

[5] 750 million gallons [15 years*50 million gallons of ethanol annually]

feet was assumed. The seed density was multiplied with the total number of required seedlings to estimate required nursery area. The value of estimated nursery area was about 1.2E-03 acres.[6]

Orchard area estimation: The required number of seeds needed to be transported to a nursery were ascertained by assuming that 15% of seeds will be damaged during transportation and other 20% will be identified as unviable during collection and processing at orchard. Therefore, total number of seeds were estimated to be 1,444. Assuming 100 seeds in a slash pine cone and 65 such cones in a bushel, the total number of bushels were estimated. Assuming a slash pine tree at a seed orchard produces 1.5 bushels/year, total number of required trees were calculated. The total plantation density at a seed orchard was found as 48 trees/acre and thus, area needed for required number of seed trees was estimated to be about 2.08E-02 acres.

Machinery use: For each practice (*orchard management*; *nursery management*; *plantation site preparation*, *planting & forest management*; and *harvesting*), different activities performed under them were identified by interviewing stakeholders. For example, under *harvesting practice* five activities were identified i.e., felling and bunching, skidding, delimbing, loading, and chipping of pulpwood and logging residue on the site. Similarly, for *plantation site preparation, planting, & forest management practice* eight activities were identified i.e., chopping, piling, burning, disking, bedding, herbicide application, planting, and fertilizer application (at year 1 and year 12 of plantation). Next, types of machines used for accomplishing identified activities under a practice were ascertained by interviewing stakeholders. The use (hours/acre) and fuel consumption (gallons/hour) rates of each machine were estimated through interviews.

[6] After taking corrections for bedding into account.

For example, it was found that machine used for loading harvested pulpwood and logging residue into chipper was TigerCat-234 whose use and fuel consumption rates were about 2 hours/acre and 4 gallons/hour, respectively. Based on these rates, total diesel consumption for each activity was ascertained. For estimating the actual amount of diesel consumed for a practice,[7] individual diesel consumption for accomplishing each activity were summed up and multiplied by the respective area.

Company catalogues were referred to estimate other necessary details of identified machines like total weight, total life, etc. For example, the total weight of TigerCat-234 (loader) was about 14 tons with an approximate life of 12,000 hours. The total weight of each machine was divided into mild steel (61.7%), aluminum (6.9%), copper (1.9%), plastics (11.2%), rubber (2.4%), cast iron (11.1%), and glass (2.9%), respectively (Burnham et al. 2006). For activities requiring special agricultural attachments, the weight of attachment was assumed as 10% of the total weight of the machine. The following formula was used for the allocation of material present in various machines: allocated material = (total material present in a machine * calculated area)/(total life of machine in hours/use rate). For example, total weight of TigerCat-234 (loader) was distributed as 10.07 tons of mild steel, 1.12 tons of aluminum, 0.31 tons of copper, 1.83 tons of plastics, 0.33 tons of rubber, 0.39 tons of cast iron, and 0.1 tons of glass. The area needed for harvesting was 1 acre. Total number of acres for which machine is useful is about 6,000 acres (total life of machine/use rate of machine). Therefore, allocated weight of mild steel present in TigerCat-234 was about 3.36 pound. This way, the allocated material use was calculated for each used machine. The

[7] Name of practices: *orchard management*; *nursery management*; *plantation site preparation*, *planting & forest management*; and *harvesting*.

individual material use for each machine was summed to obtain total material allocation for a practice.

Material use: For each practice i.e., *orchard management*; *nursery management*; and *plantation site preparation, planting & forest management*, the material use was identified by interviewing stakeholders. However, type and quantities of fertilizer use at the plantation site under the practice of *plantation site preparation, planting & forest management* was determined using Yin et al. (1998). For example, it was found that about 110 pounds/acre of fertilizer (Diammonium phosphate) was used in the first year of slash pine plantation. Similarly, fertilizer use in the 12^{th} year of plantation was found as about 66 pounds/acre of Nitrogen, 22 pounds/acre of Phosphorus, and 44 pounds/acre of Potassium. Based on the total calculated area for different practices, total quantities of material inputs were determined.

Energy use: Apart from energy used in operating different machines (mostly in the form of diesel) other energy inputs associated with practices orchard management and nursery management were also quantified. For example, it was found that certain amount of propane is used in drying seeds at the orchard. Similarly, electricity used at the nursery and orchard to store seedlings and seeds, respectively was also quantified.

Transportation: There were three transportation instances within the selected system boundary. For all instances, it was assumed that a semi-trailer would be used for transporting required cargo. Based on interviews, average distance to be traveled per trip was estimated for each transportation instance. Maximum load capacity was obtained for each semi-trailer. Required number of trips were calculated based on the total quantity of cargo to be transported at various instances. Assuming a hauling rate of

50%, the with-load and without-load fuel economies of a semi-trailer were taken as 7 miles/gallon and 8 miles/gallon, respectively. Total diesel consumption for a trip was estimated by multiplying distance traveled each side by respective fuel economies. The total diesel consumed was allocated to the transported cargo by using the formula: allocated diesel use = (total diesel consumed*weight of cargo transported)/(full load capacity of semi-trailer*number of trips required to transport required cargo). Total life of a semi-trailer was assumed as 500,000 miles. Total trips that can be made by a semi-trailer in the lifetime were calculated by dividing the total life of a semi-trailer by the total distance traveled in each trip. Based on the percentage distribution of different materials (discussed previously), quantity of each material was calculated by using the following formula for allocation: allocated material use = (total material present in a semi-trailer * weight of cargo transported)/total quantity of cargo that can be transported in the entire life of a semi-trailer. The curb weight of a semi-trailer was taken as about 8 tons. Table 3-1 provides detail of all transportation instances.

Allocation of energy and material use: Only 36% of the total biomass was utilized for ethanol production. Therefore, only 36% of all the energy and material inputs starting from the practice of harvesting to orchard management were allocated to ethanol produced. Again, it was found that the mass of produced ethanol was 81.2% of total mass of all the products produced at the mill i.e., ethanol, gypsum, methane.[8] Therefore, energy and material use was again allocated based on mass percentage of ethanol produced at the mill. This allocation was done for the steps starting from mill to the practice of orchard management.

[8] Lignin was not considered during allocation as it was reused in the mill for producing heat and electricity.

Assessing NER: The total energy needed to produce a gallon of diesel and gasoline or embedded energy was found to be 7.75 and 15.83 MJ/gallon, respectively (Furuholt 1995). Similarly, embodied energy values of other material inputs (e.g., fertilizers, cast steel, herbicides, sulfuric acid, etc.) were also ascertained. Allocated quantities of different input materials were multiplied by their embodied energy values to calculate net embodied energy use associated with the ethanol production. Additionally, the calorific values of different energy products like diesel, gasoline, and propane were found as 155.01, 131.9, and 96.87 MJ/gal, respectively. For estimating direct energy consumption, allocated quantities of diesel, gasoline, and propane were multiplied with their respective calorific values. Allocated energy consumed in the form of electricity was also considered as a part of direct energy. The calorific value of produced ethanol was taken as about 91 MJ/gallon. The total energy content of produced ethanol was divided by the sum of direct and embodied energy consumed to obtain required NER of produced ethanol.

Assessing GWI: The total emission of greenhouse gases[9] associated with the production of a unit quantity of an input (or emission factor) was obtained using SimaPra LCA software using TRACI impact factor (Bare 2003). For example, it was found that about 9 pounds of carbon dioxide equivalent greenhouse gases are emitted for producing a pound of aluminum. Similarly, emissions associated with diesel and gasoline production and consumption were ascertained. Emissions associated with electricity production were also taken into account. Carbon dioxide released during the ethanol production was also considered. Allocated quantities of different inputs were

[9] All emissions of GHGs were expressed in carbon dioxide equivalent from here onwards by following Bare et al. (2003).

multiplied by their respective emission factors to ascertain the total GWI of produced ethanol. It was found that electricity produced at the mill was in surplus and methane produced can displace natural gas production. Therefore, emissions associated with the displaced electricity from the grid and natural gas production were subtracted from the calculated GWI of the produced ethanol to estimate the net GWI.

To compare the GWI impact of produced ethanol with gasoline, it was assumed that the produced ethanol will be utilized to manufacture E85 fuel which will be further utilized in running an automobile for 150,000 miles. It was found that 3,402 gallons of E85 fuel can be produced from 2,892 gallons of ethanol after adding about 510 gallons of gasoline. Energy use and emissions associated with two additional transportation steps (*transportation of ethanol from mill to mixing plant and transportation of E85 fuel from mixing plant to the fuel pump*) were taken into account (Table 3-2). Similarly, energy and emissions associated with mixed gasoline were also considered.[10] Data from NREL (1999) was used to ascertain the total quantities of E85 fuel and gasoline consumed to run an automobile for 150,000 miles. Required quantities of E85 fuel (9,146.34 gallons) and gasoline (6,437.77 gallons) were estimated based on fuel economies of 16.4 and 23.3 miles/gallon, respectively. Total emission of greenhouse gases associated with the production of required quantities of E85 fuel and gasoline were ascertained. Using Table 3-3, emissions associated with the combustion of E85 fuel and gasoline in an automobile were obtained. The net GWI of E85 fuel was obtained by summing the GWI related with E85 fuel production and consumption, respectively. The calculated net GWI of the ethanol produced was converted to carbon

[10] The total energy required to produce a gallon of gasoline was 15.83 MJ. The total emission of greenhouse gases to produce a gallon of gasoline was about 2.33 pounds.

equivalent. Similar steps were undertaken to calculate net GWI of gasoline in carbon equivalent.

It is to be noted that total produced ethanol was derived from forest biomass which sequesters atmospheric carbon during photosynthesis. Therefore, the net allocated value of sequestered carbon was subtracted from the carbon equivalent greenhouse gas emissions associated with the production of required E85 fuel. At the same time, use of lignin in the mill as a source of heat energy displaces emissions from coal. Therefore, net saving in carbon emission due to coal displacement was also subtracted from the previously calculated carbon equivalent greenhouse gas emission value of produced E85 fuel. Furthermore, biomass used for producing ethanol was sourced from a forestland where carbon is sequestered not only in the aboveground biomass but in the soil as well. It was found that about 49.28 tons/acre of soil organic matter is available in a slash pine plantation at the age of 25 years (Gholz and Fisher 1982). Therefore, the carbon stored in soil was subtracted from the calculated value of GWI (carbon equivalent) to ascertain the net GWI of the produced E85 fuel.

Unit cost of production: The annual costs for feedstock, fuel, water, chemicals, and disposal were calculated based on the amounts of each input required to meet the annual plant capacity. Delivered feedstock costs included stumpage value to an NIPF landowner, harvesting, chipping, transportation, and profit to a logger. The value of gypsum produced was taken as $30/ton. Similarly, the value of methane was assumed as $3.59 per million Btu (EIA 2009l). All costs and benefits were scaled up to the annual capacity of the plant over the 15 year plant life to calculate the net present value of the project (Aden 2002). A real discount rate of 10% was chosen for the analysis. Although the appropriate discount rate will vary within the private sector according to the specific risk taking characteristics of the investor, Short et al. (1995) argue that 10% discount rate should be taken for projects with risks similar to renewable energy investments especially in the absence of statistical data on discount rates. The unit cost of ethanol was computed by constraining the net present value to $0.00 by allowing the price of ethanol per gallon to vary. Thus, the break even production cost per unit of ethanol was determined.

Sensitivity analysis: To analyze the impact of change in harvest age on relative percentage reduction of greenhouse gases (carbon equivalent) for E85 fuel, a sensitivity analysis was done. The harvesting age was changed from year 10 to year 35 in an interval of 1 year.

Results

The results are reported in five parts. The first part reports NER and GWI of ethanol produced at the mill. The second part reports NER and GWI of E85 fuel available at the fuel pump. In the third part, a comparison of GWI of E85 produced and consumed is made with equivalent amount of gasoline. In the fourth part the unit production cost of ethanol is reported. The last part details sensitivity analysis.

Ethanol production: Total energy use for producing 2,892 gallons of ethanol was found as 82,166 MJ. Total direct energy use was estimated to be 14,713 MJ. The maximum direct energy was consumed due to diesel consumption (about 99%). Similarly, the embodied energy use related with the consumption of various inputs was estimated to be 67,453 MJ. It was noted that the majority of total energy used within the system boundary was in the form of embodied energy (about 82%). Consumption of direct and embodied energy is shown in Figure 3-3 and Figure 3-4, respectively. As observed, the maximum amount of direct energy is consumed at the mill due to diesel consumption followed by the transportation of required biomass to the mill. It was found that maximum amount of embodied energy is also used at the mill due to consumption of diesel, construction steel, concrete, construction stainless steel, lime, water, ammonia, and sulfuric acid to produce required quantity of ethanol.[11] This was followed by the practice of *site preparation*, *planting*, *& forest management*. The NER (total output energy/total input energy) was found to be about 3.2.

The total greenhouse gas emission for producing 2,892 gallons of ethanol was found to be 41.28 tons or about 0.314 pounds/MJ of ethanol produced. This value includes greenhouse gas emissions saved due to supply of electricity produced at the mill to the grid and greenhouse gas emissions displaced due to supply of methane from the mill instead of natural gas supplied from a refinery. It does not include carbon credits generated due to displacement of coal and carbon sequestered in the biomass and soil. It was found that about 97% of all the greenhouse gas emissions were produced at the mill only followed by the practice of *site preparation*, *planting*, *& forest management* (about 1.5%). Figure 3-5 gives further details of GHG emission.

Production of E85 fuel: Total energy use for producing 3,402 gallons of E85 fuel was found as 92,468 MJ. Total direct energy was estimated to be 16,788 MJ. Maximum direct energy was consumed due to diesel consumption (about 99%). Similarly, the embodied energy use related with the consumption of various inputs was estimated to be 75,680 MJ including 8,079 MJ of energy spent on mixing 510 gallons of gasoline with 2,892 gallons of ethanol. Note that the majority of total energy used within the system

[11] The total heat energy required to produce steam was not considered as direct energy as lignin was used to produce required heat. Similarly, electrical energy used in the mill was also not considered as direct energy as electricity produced from lignin was used to meet the total electricity requirement.

boundary was in the form of embodied energy (about 81%). The consumption of direct and embodied energy is shown in Figure 3-3 and Figure 3-4, respectively. As observed, the maximum amount of direct energy is consumed at the mill followed by the transportation of required biomass to the mill. It was found that maximum amount of embodied energy is used at the mill followed by the energy spent in gasoline mixing. The NER was found to be about 3.35.

The total greenhouse gas emission for producing 3,402 gallons of E85 fuel was found as 42 tons or about 0.272pounds/MJ of E85 produced.[12] It was found that about 95% of total greenhouse gas emissions were produced at the mill only followed by the practice of *site preparation*, *planting*, *& forest management* (about 1.5%). Figure 3-5 gives further details of the GHG emission.

The greenhouse gases emitted due to production of required quantities of E85 fuel and gasoline to run an automobile for 150,000 miles were calculated as 112.64 and 7.51 tons, respectively. The total amount of tailpipe GHGs emissions were also calculated for E85 fuel and gasoline as 65.8 and 71.13 tons, respectively. These greenhouse gas emissions were added and converted into carbon equivalent. The value in terms of carbon equivalent GWI for E85 and gasoline were found to be 48.66 and 21.45 tons, respectively. The net carbon present in the allocated biomass i.e., 14.54 tons to produce 2,892 gallons of ethanol was subtracted from the total carbon equivalent GWI of E85 fuel. Similarly, carbon equivalent of displaced coal after making adjusted for allocation i.e., about 9.11 tons was also subtracted. Furthermore, allocate

[12] This value includes greenhouse gas emissions saved due to supply of electricity produced at the mill to the grid and greenhouse gas emissions displaced due to supply of methane from the mill instead of natural gas supplied from a refinery. It does not include carbon credits generated due to displacement of coal and carbon sequestered in the biomass and soil.

soil carbon present in estimated plantation area (about 14.45 tons) was also subtracted. Therefore, the overall GWI (carbon equivalent) of E85 fuel was found about 10.44 tons only. The value of GWI ratio (GWI of E85 fuel/ GWI of gasoline) was found to be 0.49 which implies that total GWI of E85 fuel is about 51% less than the GWI of equivalent gasoline.

Unit cost of production: The calculated unit cost of ethanol produced at the mill was $1.34/gallon using an average delivered feedstock cost of $30.63/green tons. Based on the lower energy content of ethanol relative to gasoline, the cost of an energy equivalent gallon of ethanol was found to be $2.05/gallon.

Sensitivity analysis: It was found that ethanol production from an acre of land is maximum i.e., 3,825 gallons when harvest occurs at year 16. The maximum reduction in greenhouse gas emissions (carbon equivalent) was found decreasing with respect to harvesting age (Figure 3-6). It was found that net reduction in GWI impact of E85 fuel with respect to gasoline is dependent on methane captured at the mill and total carbon sequestered in the soil. With respect to harvesting age, the carbon sequestered in the soil goes down and as a result of which the net reduction in GWI of E85 fuel with respect to gasoline also shows a negative slope.

Discussions

Results indicate that the NER of produced ethanol and E85 fuel is 3.2 and 3.35, respectively. Similarly, the GWI of produced ethanol and E85 fuel is 41.28 and 42 tons, respectively. It was found that GWI of production and consumption of E85 fuel in an automobile is about 51% less than the GWI of equivalent gasoline production and consumption in terms of carbon equivalent. The production cost of ethanol at the mill was found as $2.05/gallon in terms of energy equivalent gasoline.

It is to be noted that several other authors have also evaluated the environmental and energetic status of ethanol derived from various feedstocks. For example, Hill et al. (2006) found that ethanol derived from corn had a NER of 1.25 and reduces GHG emissions by 12% when compared to gasoline. Similarly, Lavigne and Powers (2007) found that ethanol derived from corn stover had a NER of about 1.7. Sabrina et al. (2005) found that use of corn stover for ethanol reduces the GWI by 65% when compared to gasoline. For ethanol derived from switchgrass, the value of NER and net reduction in GHG emissions when compared to gasoline was found as 5.4 (Schmer et al. 2008) and 90%, respectively. On comparison, the NER of E85 fuel derived from ethanol derived from slash pine biomass was found higher than the ethanol derived from corn and corn stover. However, the NER of switchgrass was found even higher than the NER of slash pine-based ethanol. The percentage reduction in GWI due to the production and consumption of E85 fuel when compared with gasoline was found higher than corn but lower than other feedstocks like corn stover and switchgrass. The results are compared in Figure 3-7.

The calculated unit price of ethanol (energy equivalent gasoline) derived from corn, corn stover, and switchgrass have been reported as $1.74/gallon ($0.46/liter) (USDA 2005), $2.08/gallon (Sheehan et al. 2004), and $2.05/gallon (Pimentel and Pimentel 2008), respectively. This implies that ethanol derived from slash pine biomass is costlier to produce when compared with corn but comparable to ethanol produced using other cellulosic feedstocks.

Conclusions

Demand for energy and food will increase in the future with the rising population of the country (EIA 2008b). Continuous reliance on imported crude oil for meeting growing energy needs will have an adverse impact on the economy as demonstrated by the recent surge in global energy prices. It is generally assumed that the utilization of biomass available on NIPFs can help in achieving goals of energy independence and reduction of greenhouse gas emissions. Therefore, the current study attempts to test the validity of this assumption by adopting a detailed life-cycle approach. A cost-benefit analysis was also conducted to ascertain the production cost of cellulosic ethanol obtained from slash pine biomass. Suitable assumptions were made to mimic a slash pine-based refinery keeping special nature of feedstock into account.

Results suggest that production of ethanol and its use in the form of E85 fuel is beneficial from the environmental perspective. However, research efforts are needed to develop suitable conversion technologies so as to reduce the cost of produced ethanol. The environmental performance of current conversion technologies like enzymatic hydrolysis or gasification-based catalytic conversion should also be tested to sure that the use of cellulosic ethanol to replace gasoline is a solution to the problem of GHG emissions. The ecological impacts of intensely-managed slash pine plantations and subsequent utilization of biomass for ethanol production were not analyzed in this study. It is expected that future research will fill this critical information gap.

Table 3-1. Details of transportation steps

Transportation steps	Code	Type	Distance Travelled (miles)		Fuel Economy (miles/gallon)		Total life (miles)	Maximum Load (tons)
			With load	Without load	With load	Without load		
Transportation of harvested biomass to mill	TR_MILL	Semi-truck	40	40	7	8	500,000	25
Transportation of seedlings to plantation site	TR_SITE	Semi-truck	50	50	7	8	500,000	25
Transportation of seeds to nursery from orchard	TR_NSY	Semi-truck	50	50	7	8	500,000	25

Table 3-2. Details of additional transportation steps

Transportation steps	Code	Type	Distance Travelled (miles)		Fuel Economy (miles/gallon)		Total life (miles)	Maximum Load (gallons)
			With load	Without load	With load	Without load		
Transportation of E85 from mixing plant to fuel pump	TR_FUEL	Tank trucks	75	75	7	8	500,000	8,000
Transportation of ethanol from mill to mixing plant	TR_MIX	Tank trucks	50	50	7	8	500,000	8,000

Table 3-3. Tail pipe exhaust of gases from an automobile

	E85 fuel		Gasoline fuel	
CO (carbon monoxide)	1.48	g/Mile	1.4	g/Mile
NOx (nitrogen oxides)	0.12	g/Mile	0.13	g/Mile
CO_2 (carbon dioxide)	396.4	g/Mile	428.9	g/Mile
CO_2 equivalent	398.72	g/Mile	431.1	g/Mile

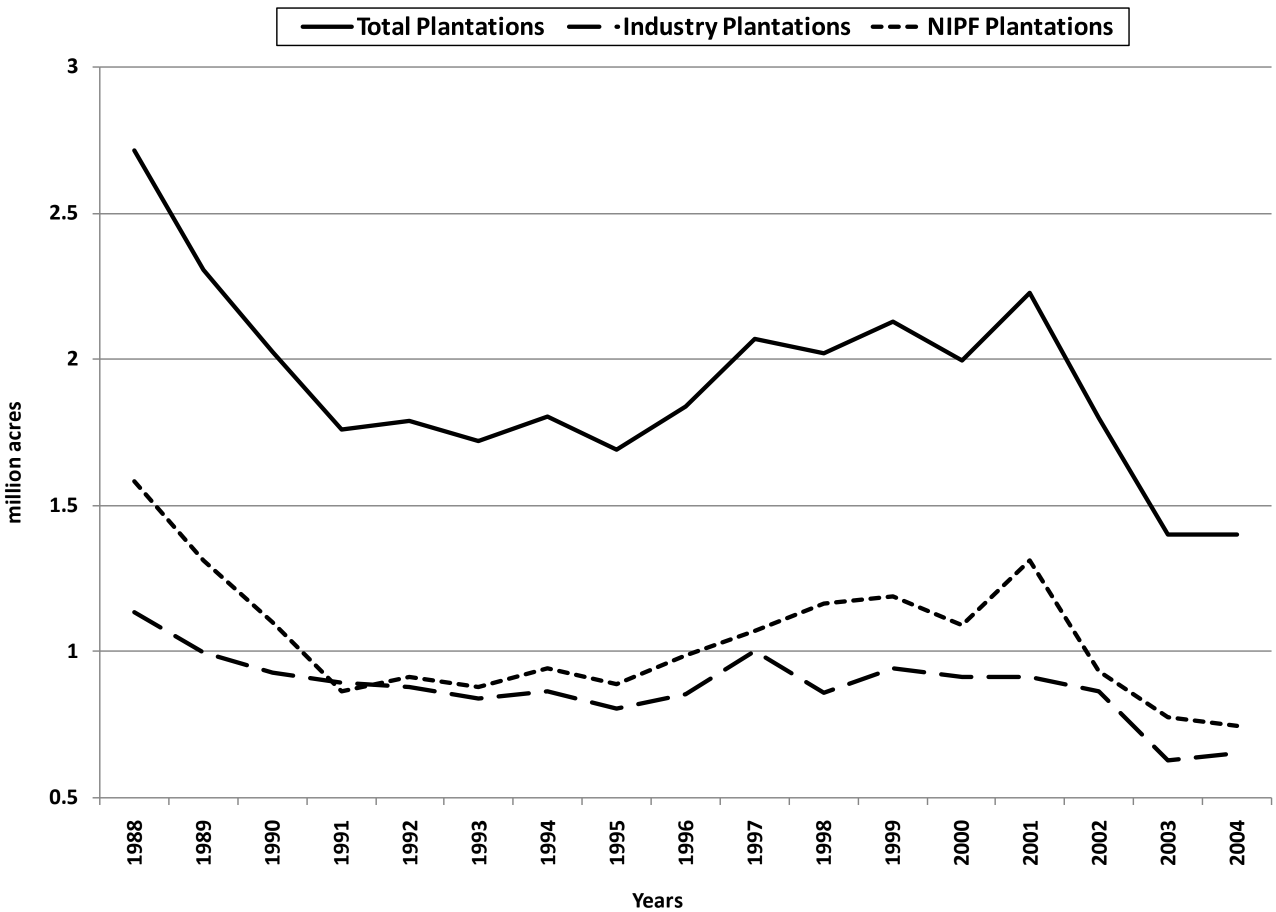

Figure 3-1. Year wise planted area (million acres) in the southern region

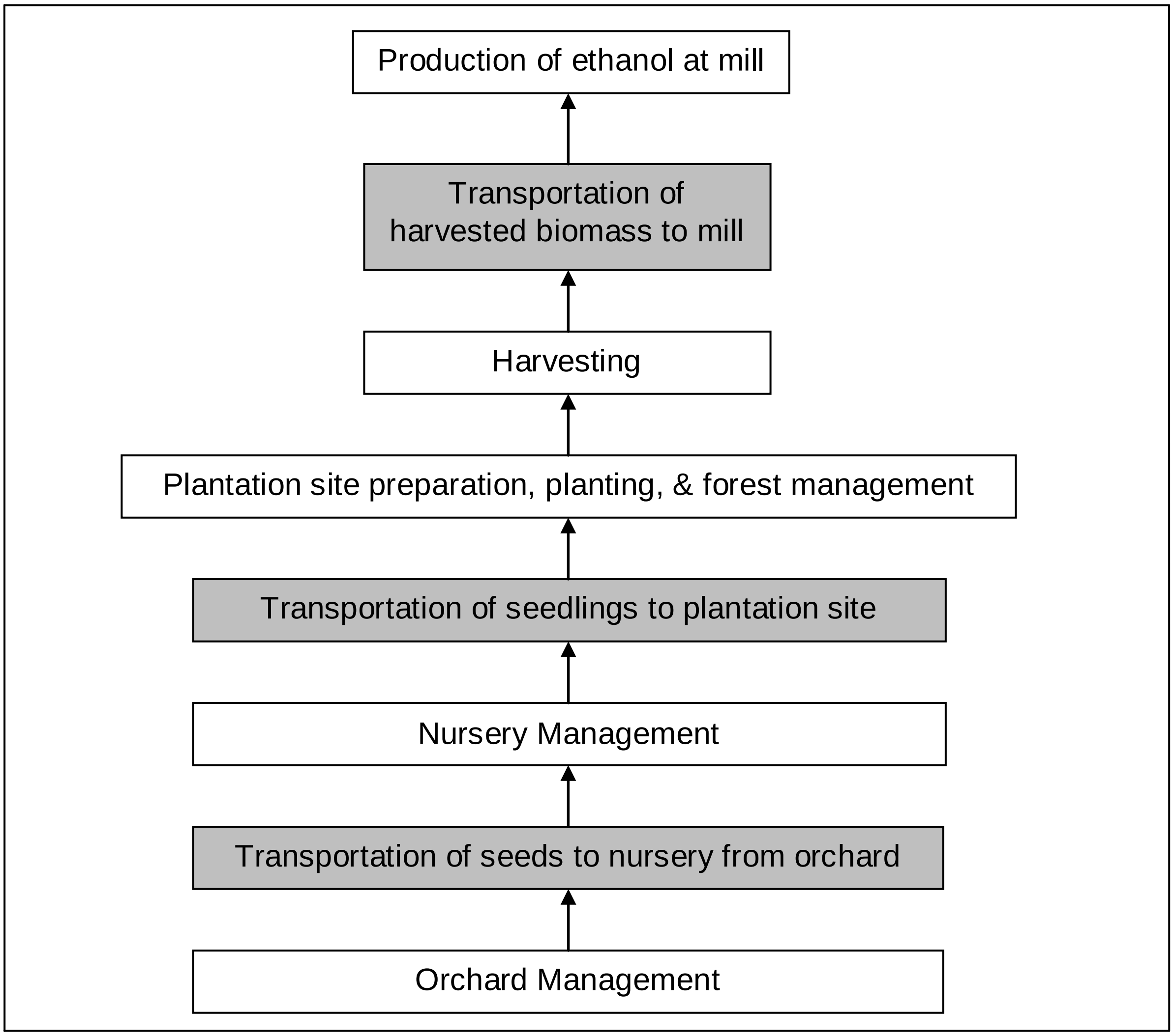

Figure 3-2. System boundary for the analysis

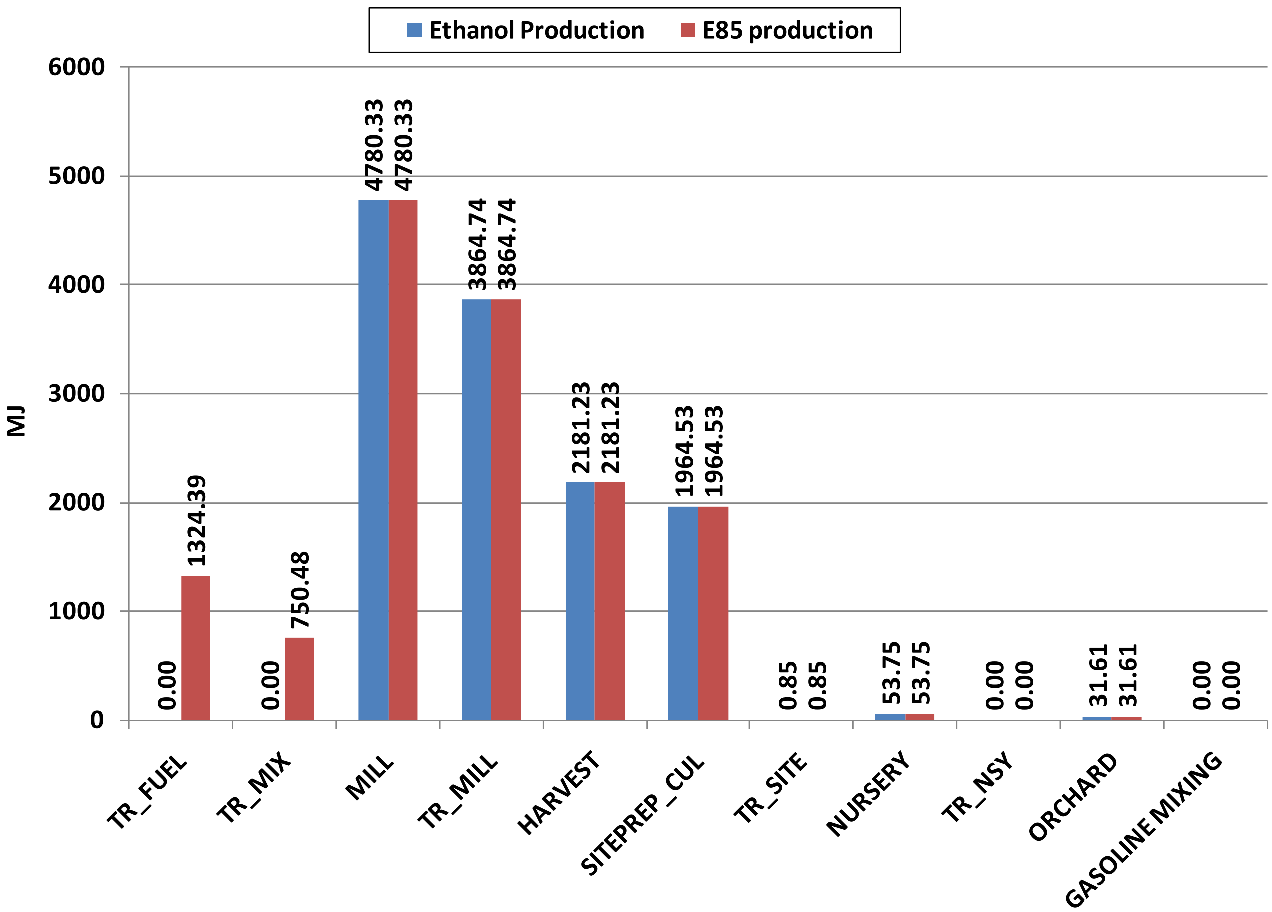

Figure 3-3. Direct energy use for the production of ethanol and E85 fuel

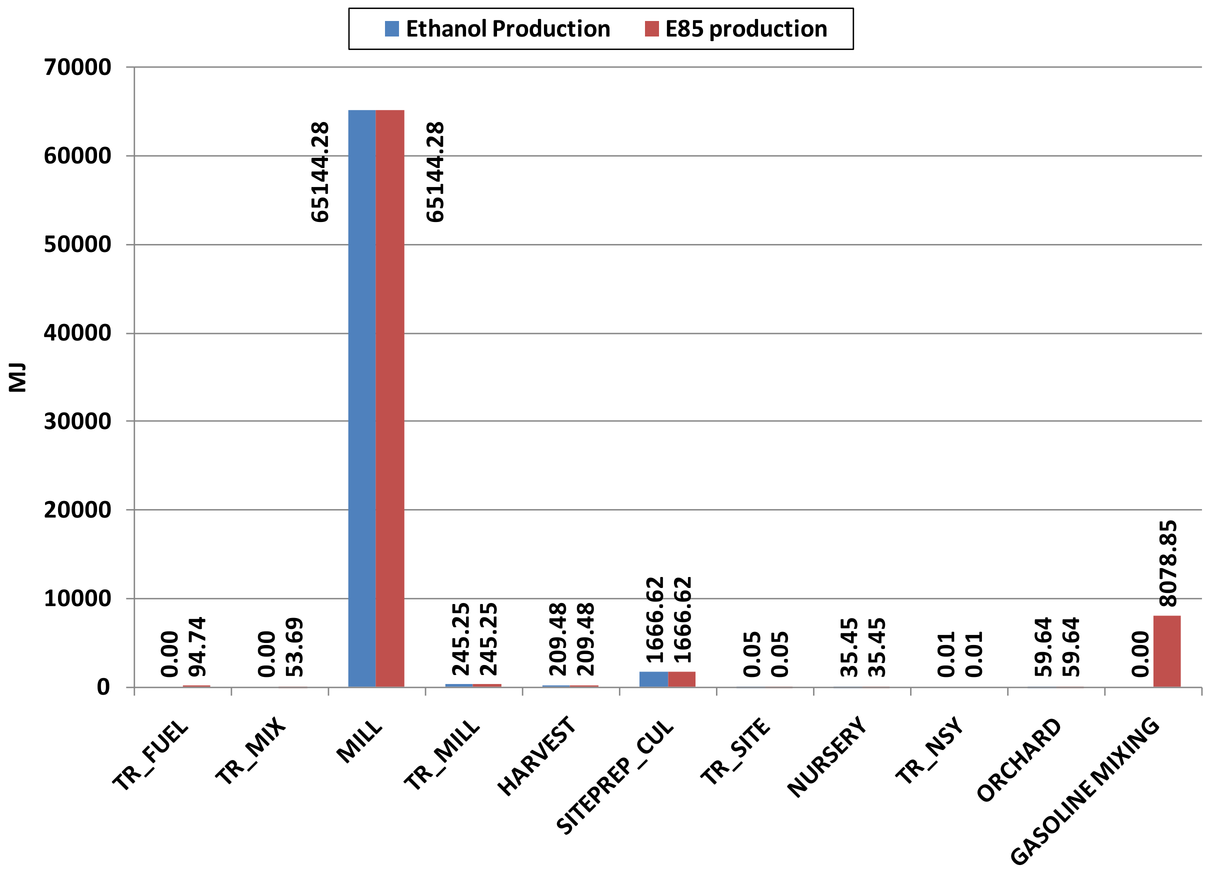

Figure 3-4. Indirect energy use for the production of ethanol and E85 fuel

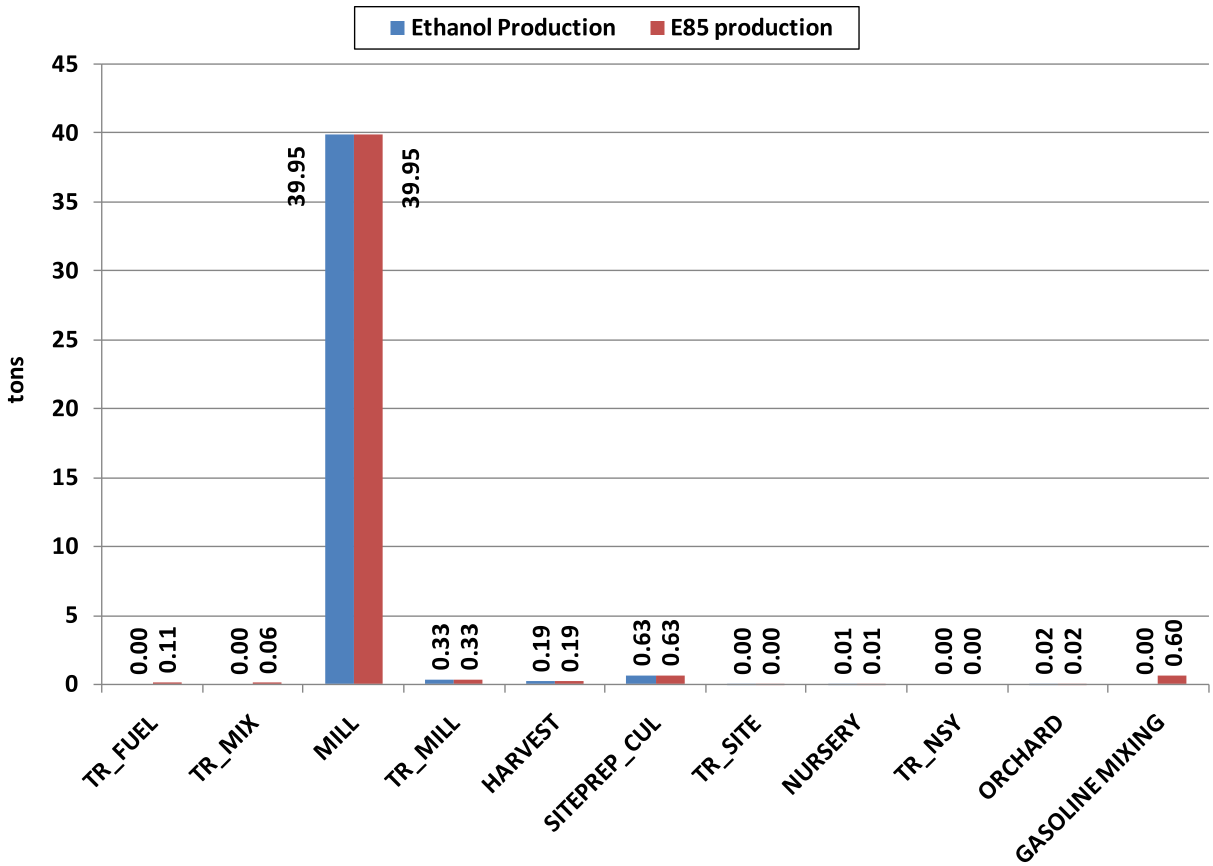

Figure 3-5. GHG emissions (carbon dioxide equivalent) due to production of ethanol and E85 fuel

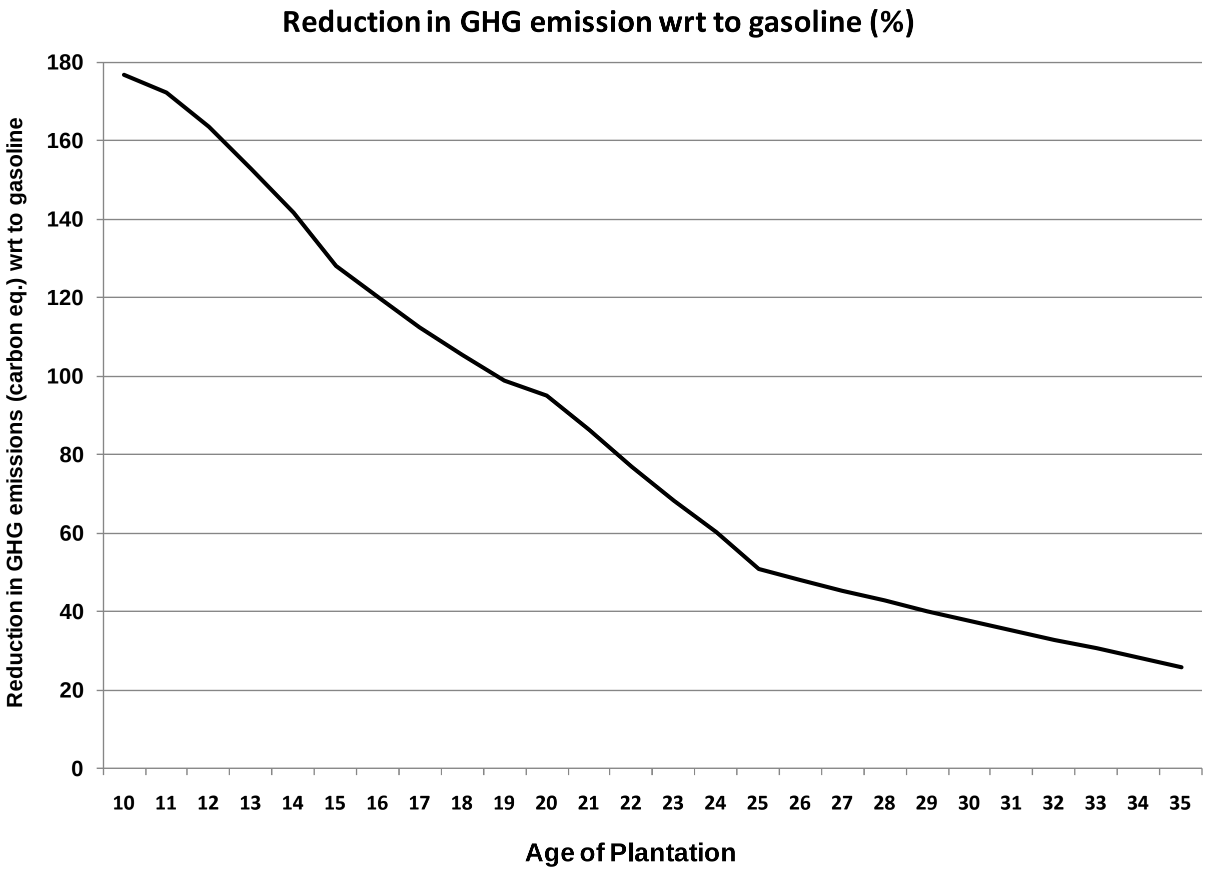

Figure 3-6. Results of the sensitivity analysis

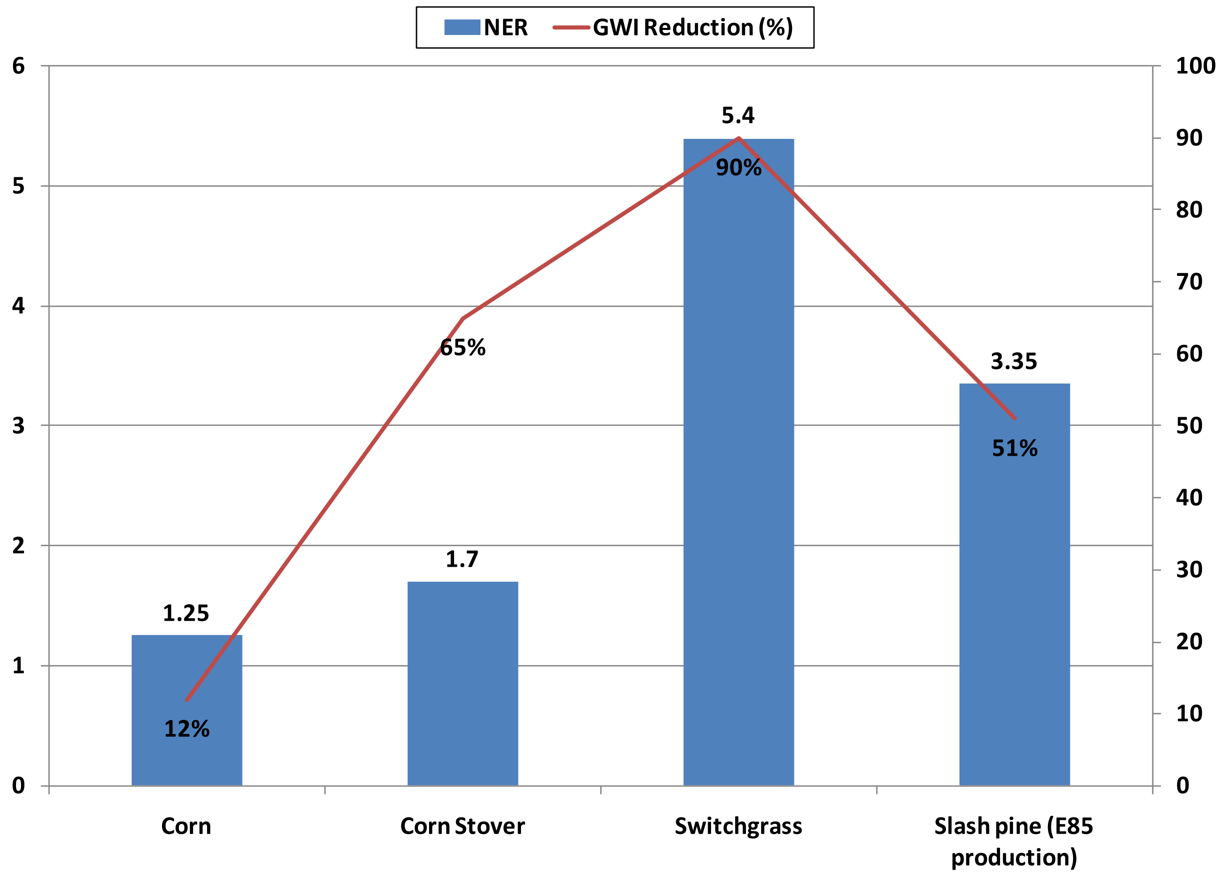

Figure 3-7. Comparison of different feedstocks

CHAPTER 4
IMPACT OF EMERGING VOLUNTARY CARBON AND BIOENERGY MARKETS ON NON-INDUSTRIAL PRIVATE FOREST LANDOWNERS' PROFITABILITY

Introduction

Forests play an important role in maintaining global climate balance by sequestering atmospheric carbon and storing it in different components like biomass, soils, etc. (Sullivan 2008). Additionally, the wood obtained from sustainable forestlands can be utilized for producing various energy products. These wood-based energy products are not only carbon neutral but can substitute for fossil-based fuels resulting in reduced emission of greenhouse gases. Encouraged by the potential role of forests and forestry products in mitigating global warming, several initiatives have been pursued by various international institutions, national governments, and individuals to promote either forest-based carbon sequestration or expedite forest biomass utilization to produce various energy products.

The United States is a leading player in utilizing forestry as a tool for reducing emission of greenhouse gases. A voluntary but legally binding market that is based on the principles of cap-and-trade (Colby 2000) has already evolved in the United States. This market, facilitated by the Chicago Climate Exchange (CCX), promotes carbon sequestration on forestlands by providing payments to forest landowners for the net carbon sequestered. The United States Congress also passed the Energy Independence and Security Act of 2007 that aims to produce 21 billion gallons of cellulosic ethanol by 2022. Forest biomass is expected to play a major role in meeting the total demand for feedstock for cellulosic ethanol production in the country because large quantities of forest biomass are available from the nation's forestlands at a reasonable price (Perlack et al. 2005).

Emerging voluntary carbon and bioenergy markets are expected to have a significant impact on the profitability of a forest landowner. Thus, this study attempts to determine the changes in the profitability of a Southern Non-Industrial Private Forest (NIPF) landowner due to the additional income provided by emerging carbon and bioenergy markets. The impact of additional income on the optimal rotation age of plantations is also analyzed. An acre of intensely managed slash pine (*Pinus elliottii*) was selected as a reference species. Slash pine is a commercial forest species that is extensively planted by NIPF landowners in the Southern United States. It is estimated that in 2005, NIPF landowners owned about 7 million acres of slash pine plantations in the Southern United States (USFS 2005).

An NIPF land located in the southern region of the United States was selected for this study as southern timberlands account for approximately 64% of the national roundwood harvest (Sun and Zhang 2006) and NIPF landowners own about 70% of timberlands in the Southern United States i.e., about 140 million acres (Smith et al. 2001). Therefore, it is expected that southern NIPF landowners and their forests will play a critical role in meeting the nationwide demand for traditional forestry products (i.e., pulpwood, chip-n-saw, and sawtimber) and cellulosic feedstocks for future bioenergy production. Similarly, the high productivity of Southern timberlands makes them more attractive for carbon sequestration projects when compared to timberlands located elsewhere in the country. Furthermore, the demand for traditional forestry products in the southern region has also recently declined. Changes in domestic consumption patterns, declining exports, increasing imports, and the depreciation or closure of older processing facilities are a few of the factors that are responsible for the decline (Wear et al. 2007). Consequently, prices of some forestry products have fallen or have become stagnant resulting in financial losses to regional NIPF landowners. It is quite likely that unsatisfactory returns from forestlands might cause NIPF landowners to sell their forestlands to some alternative land uses. Such land transformations can have severe consequences on future timber supplies and ecosystem services. Therefore, the assessment of emerging voluntary carbon and bioenergy markets in providing financial security to southern NIPF landowners is critical within the context of changing land uses.

This study is organized into seven sections. The next section provides detail of CCX guidelines for carbon payments. The third section discusses the possible role of forest biomass in meeting cellulosic feedstock demand for bioenergy development and states the assumptions of study. Analyzed scenarios are also defined. In the fourth section, the literature on the carbon sequestration potential of forests in the Southern United States, the role of carbon and bioenergy payments in determining the optimum rotation age and profitability, and total emissions from different silvicultural practices are briefly discussed. Gaps in the literature are also identified. The fifth section discusses the methodology adopted to ascertain optimum harvest age and profitability of an acre of slash pine plantation by incorporating conditions of CCX for carbon payments and payments by the bioenergy industry to a forest landowner for logging residue supply. Results of the study are presented in the sixth section. The final section discusses the results and presents the conclusions.

CCX Guidelines

Members of the CCX make a legally binding emission reduction commitment and are allocated annual emission allowances in accordance with their emission baseline and the CCX emission reduction schedule.[1] Members who reduce their emissions beyond their targets have surplus allowances to sell or bank. Those members who do not meet the emissions targets must comply by purchasing CCX Carbon Financial Instrument® (CFI™) contracts (a CFI contract is equal to 100 metric tons of carbon dioxide equivalent) (CCX 2009a).[2] Currently, the market price of a CFI contract is about $10 or $0.10 per metric ton equivalent (CCX 2009b). In addition to the CCX members, entities and individuals operating in the forestry sector can participate in the CCX by registering offsets. Such entities may join the CCX as offset providers (an owner of an offset project that registers and sells offsets directly on the exchange) or offset aggregators (an entity that serves as the administrative representative for multiple offset generating projects on behalf of multiple project owners). Before offsets from a forestry project are registered on the CCX, the project undergoes a standardized registration, verification, and crediting procedure (CCX 2009c). Three major categories of forestry projects are eligible for earning carbon offsets on the CCX—afforestation, long-lived wood products, and managed forest projects. The focus of this study is on managed forest projects, therefore, only this category will be discussed hereafter.

[1] In Phase I (2003-2006), members are committed to reduce emissions a minimum of 1% per year, for a total reduction of 4% below baseline. In Phase II (2007-2010), CCX members commit to a reduction schedule that requires year 2010 emission reductions of 6% below baseline at minimum.

[2] Carbon dioxide equivalency is a quantity that describes, for a given mixture and amount of greenhouse gas, the amount of carbon dioxide that would have the same global warming potential, when measured over a specified timescale (generally, 100 years).

Under the category of managed forest projects, the carbon accumulated in the living aboveground biomass (i.e., stem wood, stem bark, branches) and the living underground biomass (coarse root) is considered for carbon offsets. The annual net carbon accumulated is calculated by subtracting total emissions incurred during completion of different silvicultural practices (if any) plus net leakages caused by some catastrophic events (if any) from the total carbon accumulated in the living biomass (aboveground plus underground) in a year. The total annual offsets produced are based on the net carbon sequestered every year. Project owners and aggregators may earn forestry offsets for managed forest projects during 2003-2010. However, if the CCX is extended after 2010 then enrolled managed forest projects can continue to earn offsets provided the project owner expresses his or her intent of continuation with the CCX and continues to follow sustainable forestry practices. These practices must meet the standards established by organizations like the FSC (Forest Stewardship Council), the SFI (Sustainable Forestry Initiative), or the ATFS (American Tree Farm System) and must be certified by an independent certification agency.

Forestry Feedstocks

Perlack et al. (2005) estimated that about 368 million dry tons of forestland-derived biomass can be utilized for bioenergy development in the nation which is 2.5 times greater than the current consumption. This study also found that logging and other residues, fuel treatments, and fuelwood can alone contribute about 47% of total estimated biomass available from forestlands and other 53% can come from urban wood residues, wood processing residues, and pulping liquor. Similarly, Walsh et al. (2000) found that at a market price below $30/dry ton delivered, the total amount of forestry feedstocks available (excluding wood obtained from urban areas but including forest mill residues, dedicated forestry crops, and forestry residues) would account for approximately 24% of all cellulosic biomass available in the nation. However, the amount of available forestry feedstocks would increase to 45% of the total cellulosic feedstocks available at a market price up to $40/dry ton delivered. These studies clearly show that forest biomass can play a significant role in meeting the overall feedstock demand for bioenergy development.

It is hypothesized that the payments for the net carbon sequestered in forest biomass and utilization of forest biomass for bioenergy production will improve the profitability of NIPF landowners by providing extra income. It is also hypothesized that such payments will influence the optimum rotation age of plantations. Therefore, six different scenarios (Table 4-1) have been analyzed to assess the impacts of payments on profitability and optimum economic rotation age. The justification of each scenario is also explained in Table 4-1. The assumptions of the study are: CCX will continue after the end of Phase II (i.e., 2010); landowners will continue their affiliation with the CCX and will manage their forestlands based on the principles of sustainable forest management; no catastrophic events will occur; landowners will belong to the category of offset provider; NIPF landowners will use the ATFS regime for certifying their forestry practices; and only logging residue [3] obtained from forestland will be used for bioenergy production. The last assumption does not allow the use of any other type of forest product (e.g., sawtimber, chip-n-saw, or pulpwood) as a feedstock for bioenergy development. This assumption was made to address concerns of the established forest industries and, therefore, to present a more realistic scenario.

[3] Diameter at breast height ≥ 4” and to a merchantable diameter 2” outside bark.

Note that the guidelines of the CCX for calculating net carbon sequestered also take into account net carbon dioxide emitted while undertaking various silvicultural practices. Therefore, a life-cycle analysis (LCA) is integrated with a forest growth and yield model for estimating net carbon sequestered in an acre of intensely managed slash pine plantation.

Literature Review

Many studies have quantified the carbon stored in southern forestlands. For example, Brown and Schroeder (1999) estimated that eastern forests accumulated about 174 million tons of carbon annually between late 1980s and early 1990s, without accounting for carbon sequestered in roots and soils. Clark et al. (2004) studied carbon dynamics of slash pine plantations and found that the annual net ecosystem exchange of carbon dioxide was 0.26 lbs C /ft^2/yr and 0.18 lbs C/ft^2/yr at the clearcut and 0.11 lbs C/ft^2/yr and 0.12 lbs C/ft^2/yr at mid-rotation age in 1998 and 1999, respectively. Binford et al. (2006) have found that carbon was accumulated at an average rate of about 2.5 ton/acre annually in the forests of southeastern states. Their results were based on four 15 × 15 km samples of forested areas in the southeastern coastal plain region from 1975 to 2001. It was found that about 130 million tons of carbon is sequestered every year in forest biomass and soils present in the southeast and south central United States (Han et al. 2007). The authors also stated that regional forests can act as terrestrial sinks and can capture about 23% of total regional GHG emissions. All these studies suggest that southern forestlands play an important role in carbon sequestration.

Several studies have examined the impact of carbon payments on the optimal rotation age of forest plantations and associated profitability to an NIPF landowner. For example, Van Kooten et al. (1995) initially analyzed the role of carbon taxes and subsidies on the rotation age and found that the inclusion of external benefits from carbon uptake results in marginally longer optimal rotations. Alavalapati et al. (2002) have compared the profitability of longleaf (*Pinus palustris*) and slash pine timber production after incorporating payments for carbon sequestration, habitat for the endangered red-cockhead woodpecker, and other amenity benefits. They found that internalizing benefits from carbon sequestration and red-cockaded woodpecker habitat improvement alone are not enough for landowners to switch from slash pine to longleaf. Additional payments of $6.4-$13.2/acre/yr will be needed to make longleaf production financially competitive with slash pine. Stainback and Alavalapati (2002) have analyzed the role of carbon payments in determining the profitability to an NIPF landowner managing slash pine plantations. The authors concluded that carbon payments will increase the optimal rotation age, land expectation value (LEV), and the supply of sequestered carbon. In addition, they found that with the rise in value of forestland due to the presence of carbon payments, more land could be devoted to forestry as opposed to other land uses such as agriculture and urban development. In another study, Stainback and Alavalapati (2004) considered risk while estimating the role of carbon payments on the LEVs of southern forestlands. They found that risk decreases LEV and optimal rotation age of a slash pine stand at a greater rate when higher carbon prices are present as the presence of risk leads to more pulpwood production and less sawtimber production. This ultimately results in a reduction of the net carbon sequestered by trees. Further, Stainback and Alavalapati (2005) have suggested that a carbon market would induce plantation owners to increase their management intensity which may in turn have significant impacts on the amount of net carbon sequestered. None of the above studies took into account the emissions produced from various silvicultural practices while calculating LEVs and the optimal rotation age.

Vogt et al. (2005) focused on using forest biomass for bioenergy development as a potential for providing extra income to forest landowners. Recently, Nesbit et al. (2009) evaluated the role of bioenergy markets on the profitability to an NIPF landowner in the Southern United States. They found that that the bioenergy market opportunity increased land values by $28.56–$37.50/acre. It was also found that the LEV was maximized when only residues were used for bioenergy production.

Few studies have quantified the total amount of emissions generated due to use of fuel, material, and machinery while performing various silvicultural practices. Markewitz (2006) has used the LCA approach to conclude that emissions of about 1.32 tons C/acre over a 25 year rotation in an intensively managed loblolly pine (*Pinus taeda*) plantation in the southeastern United States would largely offset the expected gains in soil carbon or in pulp products due to added productivity. It was also concluded that the growth, harvest, and utilization of saw logs as timber provides a clear benefit for carbon sequestration relative to the carbon emissions incurred from intense silvicultural activities. Similarly, Johnson et al. (2005) evaluated the life cycle inventory (LCI) of different compounds which are released into the atmosphere due to the use of fuel in thinning and harvesting operations for forests located in southeastern and pacific northwest regions of the United States. The authors found that transportation-related activities and the use of diesel fuel produced by far the largest contribution to emission outputs. However, fertilizer use also contributed to much of the change in emissions as acreage shifted to higher intensity management alternatives. White et al. (2005) also evaluated the LCI of round wood production in northern Wisconsin. The authors noted that carbon budgets for the harvesting process of the Chequamegon-Nicolet National Forest, the Northern Highland American Legion State Forest, and non-industrial private forests that participated in the managed forest laws of Wisconsin were 0.04, 0.07 and 0.04 tons C/acre/yr, respectively. It was also found that forests act as a net carbon sink even after including emissions from fossil fuels.

The above literature review suggests information is required on the simultaneous impact of emerging voluntary carbon and bioenergy markets on the profitability of an NIPF landowner and the optimum rotation age of their plantation. This study attempts to fulfill the research gap by developing a case study for an acre of intensely managed slash pine plantation in the Southern United States. In particular, the study uses LCA to ascertain the total GHGs produced (carbon dioxide equivalent) from various silvicultural practices undertaken to produce slash pine biomass. Then, the LCA and slash pine growth and yield modeling results are integrated with a modified Faustmann formula to assess the impacts of carbon and bioenergy payments on the rotation age and profitability.

Methods

This section has three parts. The first provides details about the methodology adopted for ascertaining the carbon balance of a slash pine plantation. The second part describes necessary steps involved in estimating total emissions of GHGs (carbon dioxide equivalent) from different silvicultural practices. Finally, the third part explains the methodology for deriving the optimal rotation age and profitability. In view of the uncertainty associated with the cost of registering carbon credits at CCX and carbon prices, a sensitivity analysis was also conducted for all the scenarios.

An acre of forestland with no initial carbon stock was defined as the unit of analysis. A growth and yield model was used for ascertaining total biomass availability from an acre of slash pine plantation (Yin et al. 1998). Using the approach of Pienaar and Rheney (1993), the growth and yield model was suitably modified to accommodate thinning at the 12th year of the plantation.[4] The CO2FIX model was adopted for ascertaining the carbon balance of the plantation (Schelhaas et al. 2004). However, out of the four components of the CO2FIX model, only biomass and soils were considered in this study and the remaining two (round wood products and bioenergy) were excluded because the CCX guidelines for managed forest projects do not consider round wood products and bioenergy for calculating net carbon sequestered. The model used for ascertaining the carbon balance in the plantation is explained in Figure 4-1. Different parameters that were used at various steps are also shown in Figure 4-1.[5] Stem biomass was parameterized using the growth and yield model. To parameterize foliage, branch, and root biomass with respect to stem biomass, suitable ratios were calculated from Gholz and Fisher (1982). A turnover rate for each biomass component was derived to estimate the availability of annual dead biomass. Annual turnover rates for foliage, branches, and roots were assumed to be 0.5, 0.082, and 0.014 respectively (Cropper and Gholz 1993). The turnover rate for stem biomass was assumed equal to

[4] Site index was set at 70 feet at year 25 and the number of seedlings at the second year of the plantation was 700/acre.

[5] Exposure rate (ER) is defined as the percentage of dead biomass available for decomposition every year.

the natural mortality rate of trees in a plantation. The CO2FIX model uses the YASOO model for ascertaining fluxes and stocks of carbon in the soil. The YASOO model consists of three litter compartments describing the physical fractionation of litter and five compartments describing microbial decomposition and humification processes in the soil (Masera et al. 2003). The percentage distribution of extractive, cellulose, and lignin present in the three litter compartments-coarse woody residues, non-woody residues, and fine woody residues-were obtained from Howard (1973). All other required parameters of the study were adapted from Liski et al. (2005) as exact values of parameters for slash pine were not available. However, the largest values (from a given range) were considered in the analysis to account for the relatively warm climate of the Southern United States. For calculating carbon present in live biomass, the carbon percentage was assumed to be 50% by weight (Ω).

Silvicultural practices (and activities under each practice) were identified based on Yin et al. (1998). Details of identified silvicultural practices and activities under each practice are—site preparation (chopping, piling, burning, disking, bedding, herbicide application, and planting), cultural operations (fertilization, twice), mechanized thinning[6] (felling & bunching, skidding, delimbing, and loading), and mechanized harvesting (felling & bunching, skidding, delimbing, and loading). For determining the total material and machinery usage in identified silvicultural practices, personal interviews were conducted with four loggers and five landowners. Based on usage rates of different machines (hr/acre) and their diesel consumption (gallons/acre), total diesel consumption was estimated for each activity. Net emissions associated with the manufacturing of

[6] While analyzing the scenario of no thinning, GHG emissions (CO_2 equivalent) from the mechanized thinning were not included.

each material used (diesel, gasoline, herbicides, and fertilizers) were calculated from the Franklin Database available with SimaPro 7.1 Multiuser. Similarly, total emissions related with the combustion of gasoline and diesel were also derived. For assessing total quantities of carbon dioxide equivalent emissions for each forestry practice, the TRACI database was used (Bare 2003).

Faustmann (1995) derived the formula for ascertaining the LEV of a forest in perpetuity. The Faustmann equations is as follows:

$$\boldsymbol{LEV(t) = \frac{val(t)e^{-rt} - C}{1 - e^{-rt}}} \qquad \text{[Eq. 4-1]}$$

where *LEV(t)* is the land expectation value or the present value of profit from growing an infinite number of rotations of trees, *r* is the real discount rate, *C* is the cost of establishment, and *t* is the Faustmann rotation that maximizes the sustained annual net timber revenues from using the land in forestry. The variable, *val(t)*, which is the annual net timber revenue, is derived as:

$$\boldsymbol{val(t) = p_{st}Q_{st}(t) + p_{cs}Q_{cs}(t) + p_{pw}Q_{pw}(t) + p_{lr}Q_{lr}(t)} \qquad \text{[Eq. 4-2]}$$

where prices and quantities of saw timber, chip-n-saw, pulpwood, and logging residue are presented by p_{st}, Q_{st}; p_{cs}, Q_{cs}; p_{pw}, Q_{pw}, and p_{lr}, Q_{lr}, respectively.

Following Hartman (1976) and Nguyen (1979), the net present value of non-timber benefits, *pvk(t)* over the length of the rotation are represented by:

$$\boldsymbol{pvk(t) = \int_0^t k(t)e^{-rt}dt} \qquad \text{[Eq. 4-3]}$$

where *k(t)* is a function of non-timber benefits derived from the stand before harvest. These benefits can include water quality, wildlife habitat or recreational values. The modified Faustmann model with timber and non-timber benefits becomes:

$$\boldsymbol{LEV(t) = \frac{val(t)e^{-rt} - C + pvk(t)}{1 - e^{-rt}}} \qquad \text{[Eq. 4-4]}$$

The total carbon present in the live biomass, forest floor litter, compounds (extractive, cellulose, lignin) and total carbon lost due to decay of compounds from an acre of slash pine plantation were estimated using a modified CO2FIX model. The present value of carbon benefits of a growing stand was then represented by:

$$\boldsymbol{pvc(t) = \int_0^t p^c v'(t) e^{-rt} dt - dec^{compounds}} \qquad \text{[Eq. 4-5]}$$

where p^c is the price of carbon and $v'(t)$ is the derivative of the volume function. The decay rate of compounds was presented as:

$$\boldsymbol{dec^{compounds} = \int_0^t p^c Q^{compounds} e^{-rt} dt} \qquad \text{[Eq. 4-6]}$$

where $Q^{compounds}$ is the total quantity of carbon that decays and is lost into the atmosphere. Similarly, the present value of other amenities (e.g., hunting leases) can also be represented by:

$$\boldsymbol{pva(t) = \int_0^t p^h e^{-rt} dt} \qquad \text{[Eq. 4-7]}$$

where p^h is the price of other amenities. The resulting model is represented as:

$$L\boldsymbol{EV(t) = \frac{val(t)e^{-rt} - D + pvc(t) + pva(t)}{1 - e^{-rt}}} \qquad \text{[Eq. 4-8]}$$

where *D* equals *C* plus the penalty due to carbon released at the time of execution of different practices, annual taxes, annual management costs, annual certification costs, and the costs incurred due to cultural practices.[7] Table 4-2 summarizes the cost estimates of different forestry operations and Table 4-3 gives details of the prices of different revenue streams used in this study. The real discount rate was fixed at 5%.

Results

The growth of various forestry products with and without thinning is shown in Figure 4-2. As shown, the growth of sawtimber is higher in a thinned plantation when

[7] All these values have been discounted back to year zero for analysis purposes.

compared with an unthinned slash pine plantation. However, growth of other timber products (i.e., chip-n-saw, pulpwood, and logging residue) decreases with thinning.

Annually sequestered carbon for different scenarios without considering emissions is shown in Figure 4-3. As expected, carbon stored at the system level is always higher than carbon stored in the live biomass for both the scenarios of with and without thinning. It is also evident that carbon stored at the system level in a thinned plantation (after thinning) is smaller than the carbon stored at the system level in the corresponding unthinned plantation. The same result was also observed for the carbon stored in the live biomass.

Total emissions from an acre of slash pine plantation in terms of carbon dioxide equivalent from different silvicultural practices are reported in Table 4-4. In case of an unthinned plantation, the use of fertilizers was found to be significant by accounting for 41.6% of total emissions, followed by emissions incurred at the time of harvesting. However, for a thinned plantation the emissions produced from thinning and harvesting were greater than the emissions produced from fertilizer use.

The LEVs and corresponding optimal rotation ages for identified scenarios are summarized in Figure 4-4. When compared to the base scenarios of A and B, the LEV for scenarios C and D were higher by 49% and 50%, respectively. Similarly, the LEVs for scenarios E and F were higher by 51% and 52% when compared to the base scenarios of A and B, respectively. The optimal rotation age for all the scenarios was 22 years.

Results of the sensitivity analysis in which carbon prices were varied from $0.1 to $7.4 (the highest price on CCX) in an interval of $1 are reported in Table 4-5. Similarly, the registration price of carbon credits at CCX was also varied from $25 to $125 in an interval of $25 and the results are shown in Table 4-5. Furthermore, prices of logging residue are varied from $1 to $10 in an interval of $1.[8] The sensitivity analysis proves that with an increase in carbon and logging residue prices, the LEVs will increase considerably. Similarly, the variation in registration cost affects the LEVs. However, even when the registration cost of carbon credits at CCX were high, the LEVs were higher than the LEVs of the base scenarios (i.e., scenarios A and B). However, it is advisable for small landowners to participate in an offset aggregator project to further reduce the cost of registration and certification.

Discussions

Results indicate an increase in profits to an NIPF landowner even at a low prices of carbon ($0.1/metric ton of carbon sequestered) and logging residue ($5/ton). It was also found that in presence of logging residue and carbon payments, the thinning of plantations will yield more benefits to private landowners especially when prices of carbon are low. Several authors have identified that thinning increases benefits to landowners. For example, Dwivedi et al. (2009) analyzed the role of carbon payments on the optimal rotation age and profitability of slash pine plantations and found that thinning increases the net profitability. Susaeta et al. (2009) analyzed the role of bioenergy payments and found that thinning increases landowners' profitability. Therefore, the results of the study were found congruent with the results of other studies.

[8] For each sensitivity analyses, the other factors were not changed and only changes in the LEV and optimal rotation age of scenarios E and F were recorded.

No change is the optimal rotation age was observed. This implies that in the presence of carbon penalties for emissions related to various silvicultural operations and decomposition, it is not necessary that the optimal rotation age will change. This also implies that there will be no change in timber supplies even in the presence of carbon and logging residue payments.

We found that even at a high cost of registering carbon credits at CCX, profitability was higher when compared to the base case scenarios. This implies that introduction of carbon and logging residue payments will be helpful to NIPF landowners. It was also found that at higher carbon prices, the LEV of an unthinned plantation was more than the LEV of a thinned plantation. This was primarily due to emissions of GHGs at the time of undertaking thinning and also due to large accumulation of carbon in an unthinned plantation when compared to a thinned plantation.

Conclusions

This study analyzed the impact of emerging voluntary carbon and bioenergy markets on the optimal rotation age of a forest plantation and the profitability to an NIPF landowner. An acre of intensely managed slash pine plantation was selected as a unit of analysis. The CCX guidelines of carbon payments under the managed forest projects category were simulated along with payments for logging residue produced on forestland for assessing the aforementioned impacts. LCA and an updated version of a forest growth and yield model were integrated with a modified Faustmann model to achieve this task. The LCA approach was used to obtain the total emissions associated with different silvicultural practices. Similarly, an updated version of a forest growth and yield model was used for ascertaining the carbon balance inside an acre of slash pine plantation. This model mimics the growth of the biomass in branches, roots, and foliage with respect to growth in stem biomass. Also, the model was found helpful in ascertaining soil carbon.

Payments from emerging carbon and bioenergy markets will increase profitability of NIPF landowners and thus can help in preventing unwanted land use change, ensuring sustainable timber supplies, and maintaining the ecological integrity of the region. With significant numbers of NIPF landowners in the region, carbon markets have considerable potential to sequester large amounts of carbon from the atmosphere at a minimum cost. Similarly, use of forest biomass-based energy products can help in reducing GHG emissions to the atmosphere. Based on this potential, it would be beneficial to adopt a suitable policy to expand the role of forestry in climate change mitigation. The role of other mechanisms as provided by CCX (i.e., afforestation and long-lived wood products) should also be analyzed to assess their efficacy in promoting benefits to NIPF landowners and mitigating the negative impacts of GHG emissions.

The present study did not consider risk of natural calamities (e.g., insect attacks, hurricanes, etc.) in the analysis. Furthermore, because silvicultural practices vary considerably among NIPF landowners, results obtained in the study can only be applicable given the assumptions adopted here. Results will likely vary with adopted silvicultural practices and ecological characteristics of forestland.

Table 4-1. Scenarios for the study

	Scenario A	Scenario B	Scenario C	Scenario D	Scenario E	Scenario F
Intensive management	Yes	Yes	Yes	Yes	Yes	Yes
Thinning	Yes	No	Yes	No	Yes	No
Payment for logging residue	No	No	Yes	Yes	Yes	Yes
Emissions	No	No	Yes	Yes	Yes	Yes
Payments for carbon sequestration	No	No	Live	Live	System	System

Intensive management: NIPF landowners will prefer fast growth of slash pine plantation as carbon and bioenergy payments are dependent on net biomass growth. As a result, intensive management of plantations is considered in all the six scenarios.

With and without thinning: Majority of NIPF landowners are not thinning their forestlands due to low prices of traditional forest products. Therefore, understanding the role of payments under both the scenarios of with and without thinning becomes even more critical. Thinning is assumed to be done at the 12th year of plantation.

Payment for logging residue: Scenarios of with and without logging residue payments are considered to assess the impacts on profitability and optimal rotation age.

Emissions: GHG emissions associated with energy use on forest site are calculated using life-cycle analysis. Then, scenarios of with and without emission penalties are tested to assess the impact on profitability and optimal rotation age.

Payments for carbon sequestered: Guidelines of CCX only consider payments for that carbon which is sequestered in the live biomass (underground and aboveground). However, carbon stored in foliage, litter, and decaying matter is significant too. Moreover, carbon is also lost to the atmosphere due to decomposition of dead biomass. Therefore, two scenarios of carbon payment i.e., live (stem with bark, branches, and coarse root) and system (live, foliage, litter, soil, decomposition into carbon dioxide) are considered.

Table 4-2. Details of cost streams

Activities	Frequency	Cost estimates ($/acre)
Site Preparation:		
Chopping	Year 0	50
Piling	Year 0	48
Burning	Year 0	60
Disking	Year 0	100
Bedding	Year 0	105
Herbicides	Year 0	60
Planting	Year 0	90
Cultural operations:		
Initial Fertilization	Year 1	80
Second Fertilization	Year 12	100
Certification:		
Registration in CCX	Year 0	100
Registration for certification scheme	Year 0	20
Annual inspection	Annual	10
Other:		
Taxes	Annual	7
Management	Annual	5

Cost data: M. Simpson, (personal communication, 2008)
Certification costs: C. Myers, (personal communication, 2009)

Table 4-3. Details of revenue streams (TMS 2009)

Price of Carbon	$0.1/metric ton
Timber products	
Sawtimber	$28.55/ton
Chip-n-saw	$14.99/ton
Pulpwood	$8.97/ton
Logging residues	$5/ton
Amenities	$20/year/ac

Table 4-4. Emissions (lbs/acre carbon dioxide equivalent) from silvicultural practices

Silvicultural Practices	Emissions	
	Unthinned plantation	Thinned plantation
Site preparation	1,014	1,104
Thinning	-	1,436*
Harvesting	1,795	1,615.5**
Cultural operations	2004	2004
Total	4,813	6,249

*Emissions related to thinning were taken as 80% of harvesting.
**Emission related to harvesting in a thinned plantation was taken as 90% of emissions related to harvesting in an unthinned plantation.

Table 4-5. Sensitivity analysis for Scenario E and Scenario F

		Unthinned Plantation		Thinned Plantation	
	Prices	LEV$^{\alpha}$ ($/acre)	ORA$^{\beta}$ (years)	LEV ($/acre)	ORA (years)
Carbon prices at CCX ($/tonne)	0.1	176	22	213	22
	1.1	355	22	358	22
	2.1	537	21	505	21
	3.1	718	21	652	21
	4.1	899	21	799	21
	5.1	1,081	21	946	21
	6.1	1,262	21	1,093	21
	7.1	1,446	20	1,240	21
	7.4	1,501	20	1,284	21
Registration prices at CCX ($/acre)	25	289	21	327	21
	50	251	22	288	21
	75	214	22	250	22
	100	176	22	213	22
	125	139	22	175	22
Logging residue prices ($/ton)	1	142	22	167	22
	2	151	22	179	22
	3	159	22	190	22
	4	168	22	201	22
	5	176	22	213	22
	6	185	22	224	22
	7	193	22	236	21
	8	202	21	249	21
	9	211	21	261	21
	10	221	21	274	21

α: Land Expectation Value
β: Optimal Rotation Age

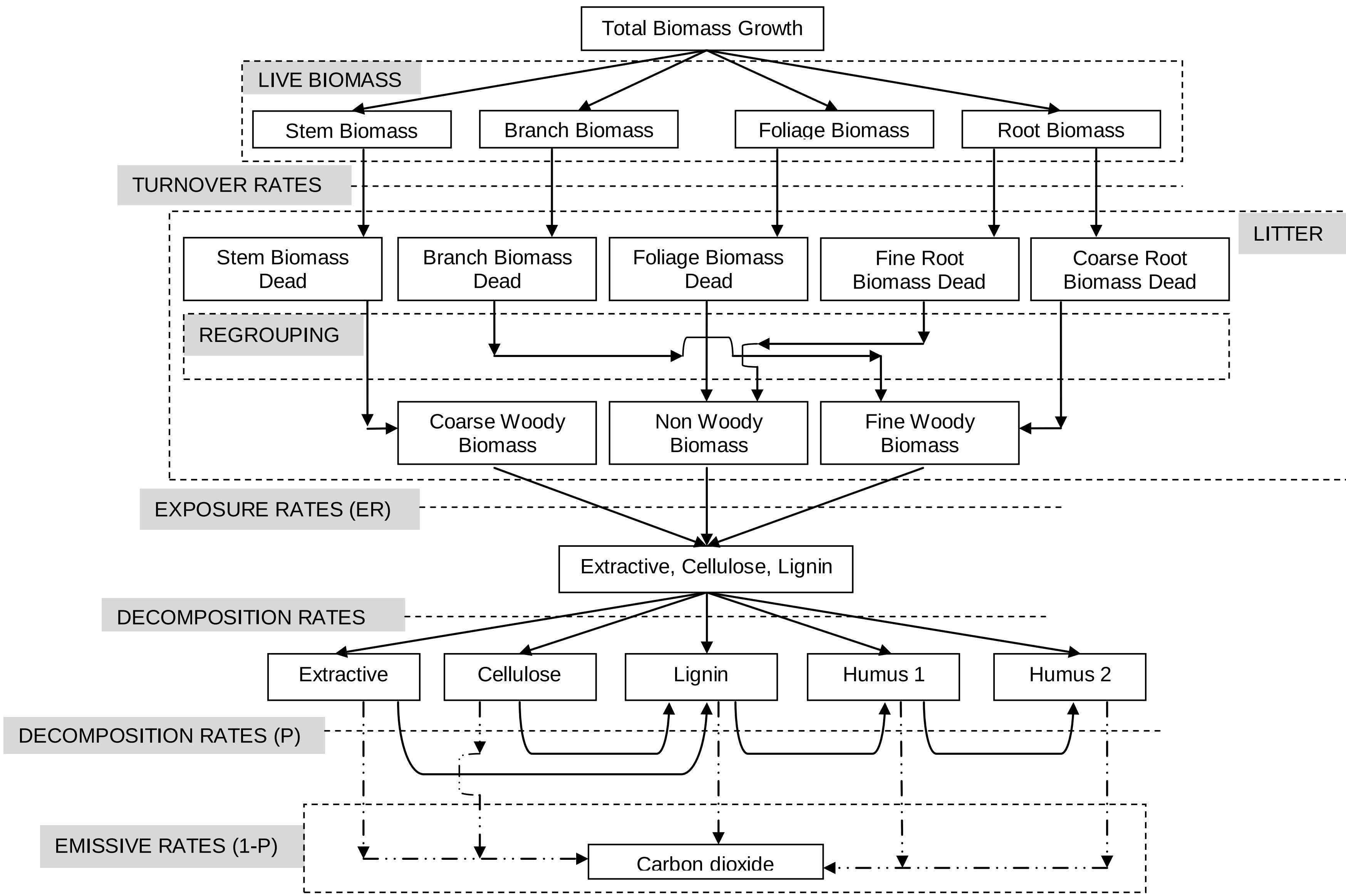

Figure 4-1. Model used for assessing carbon balance in slash pine plantations

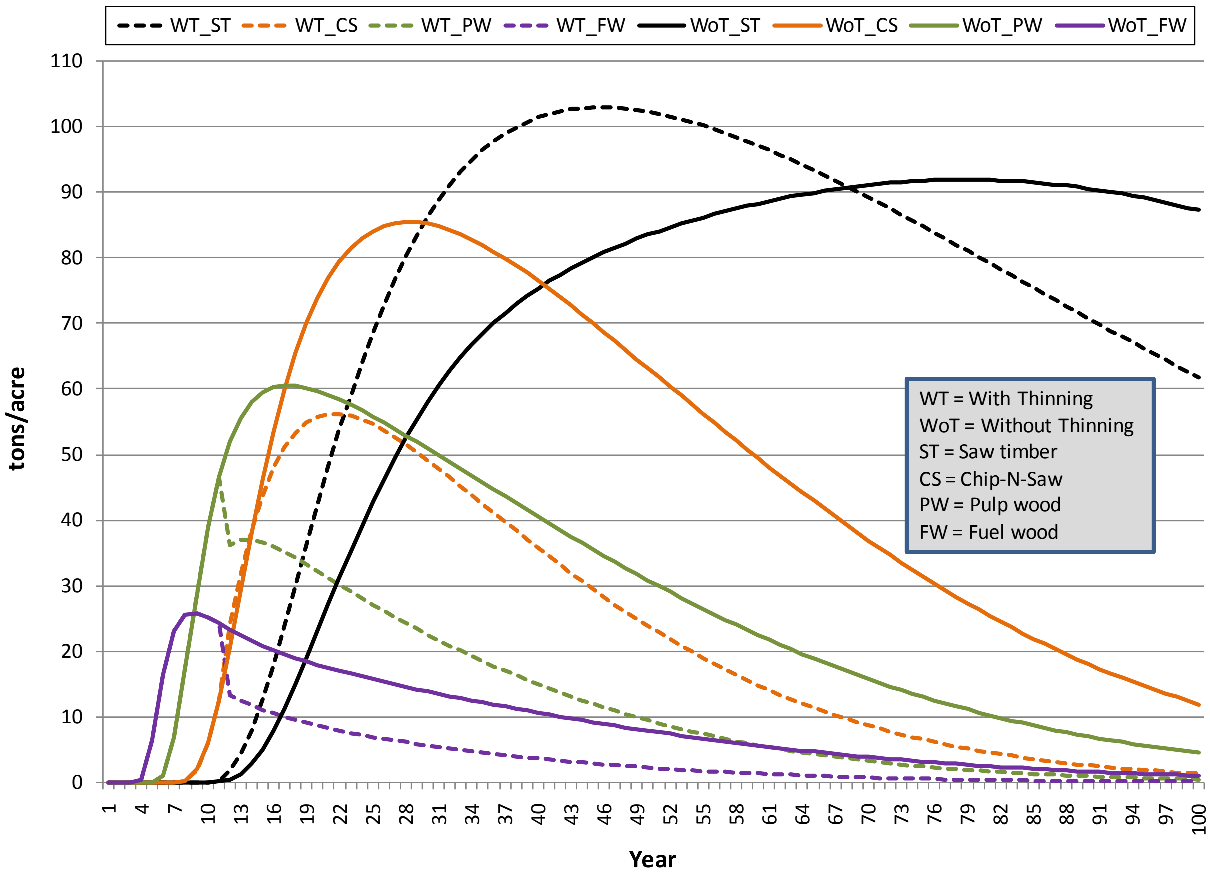

Figure 4-2. Biomass distribution in different products for a thinned and an unthinned slash pine plantation

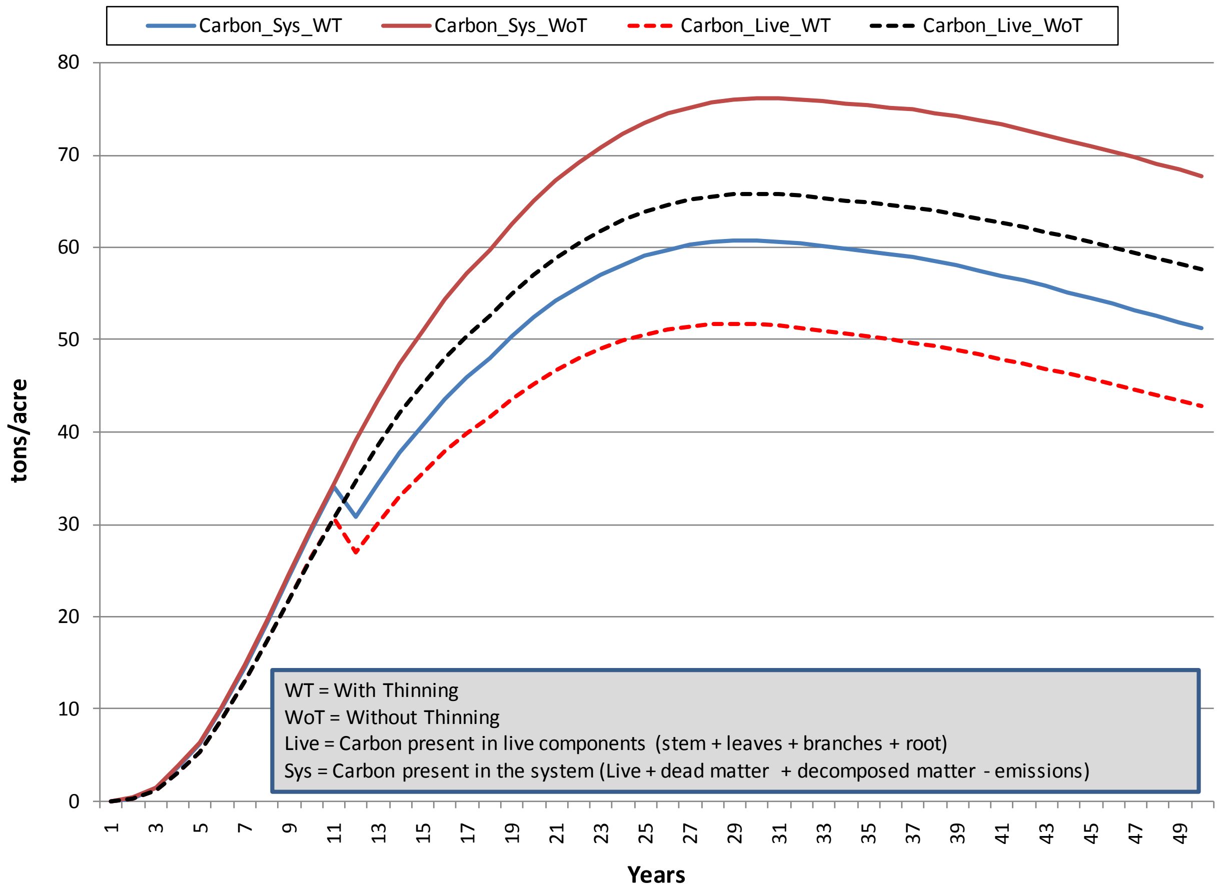

Figure 4-3. Carbon distribution for a thinned and an unthinned slash pine plantation

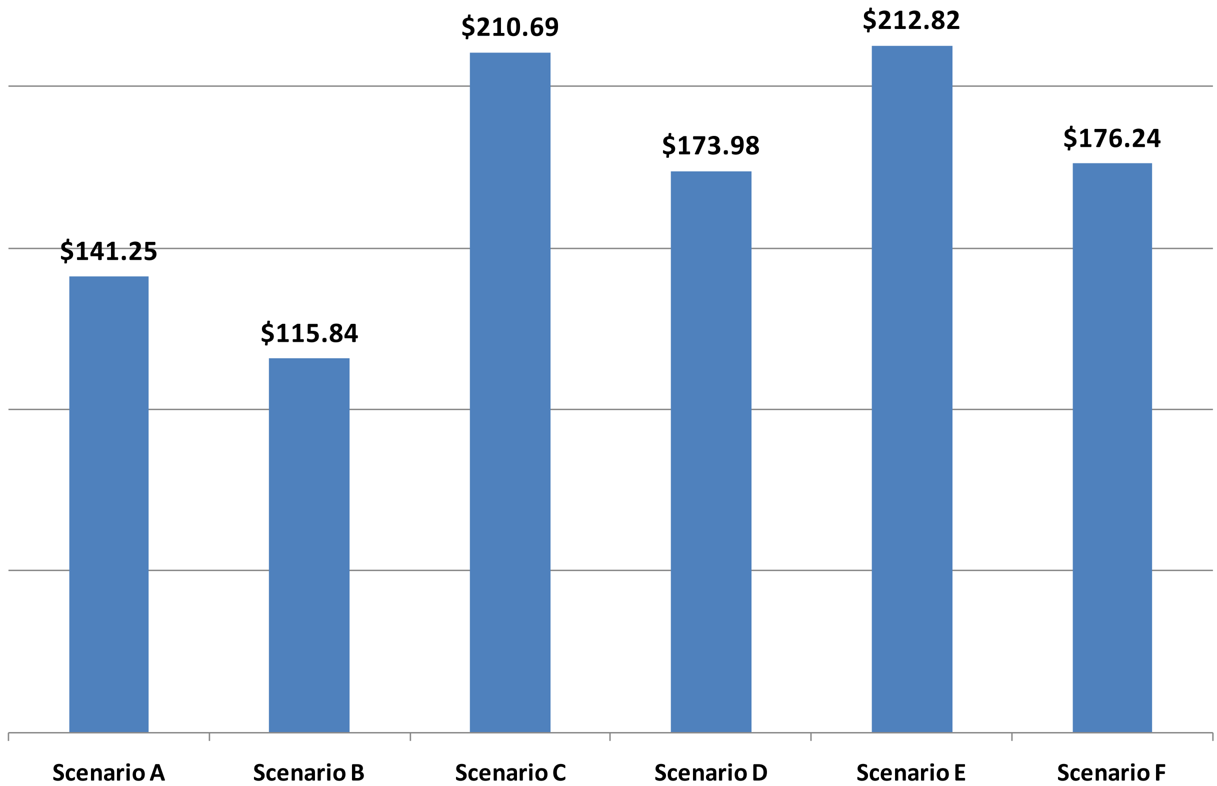

Figure 4-4. Calculated LEVs of different scenarios

CHAPTER 5
STAKEHOLDERS' PERCEPTIONS ON FOREST BIOMASS-BASED BIOENERGY DEVELOPMENT IN THE SOUTHERN UNITED STATES

Introduction

The Energy Independence and Security Act of 2007aims to produce 21 billion gallons of cellulosic biofuel by 2022 in the United States. Additionally, the recently enacted the Food, Conservation, and Energy Act of 2008 provides a subsidy of $1.01 on every gallon of cellulosic ethanol. Furthermore, many state and privately owned companies are making investments to produce electricity and ethanol by using cellulosic biomass as a feedstock. For example, the Gainesville Regional Utilities is building a 100 MW power plant in Gainesville, Florida that will primarily utilize cellulosic biomass for electricity production (GRU 2009). Similarly, Range Fuels is building an ethanol plant in Soperton, Georgia to produce 100 million gallons of ethanol per year using various cellulosic feedstocks (Range Fuels 2009). It is expected that the growing interest in utilizing cellulosic feedstocks to meet present and future energy needs will create a high demand for the resource.

Forestlands occupy about 747 million acres of the total geographic area of the United States (Smith et al. 2001) and could contribute significantly to the supply of cellulosic biomass for bioenergy development. Walsh et al. (2000) found that at a market price below $30/dry ton delivered, the total amount of forestry feedstocks available (excluding wood obtained from urban areas but including forest mill residues, dedicated forestry crops, and forestry residues) would account for approximately 24% of all cellulosic biomass available in the nation. However, the amount of available forestry feedstocks would increase to 45% of the total cellulosic feedstocks available at a market price of up to $40/dry ton delivered. The role of timberlands present in the Southern

United States (Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, Missouri, North Carolina, Oklahoma, South Carolina, Tennessee, Virginia, and West Virginia) in meeting the national forest biomass demand is critical. Southern timberlands occupy approximately 140 million acres and supply the majority of all harvested forest biomass in the country. For example, in 1997 the southern forestlands supplied about 64% of the total forest biomass harvested in the country i.e., 9.5 billion cubic feet (Smith et al. 2001).

At present, forest landowners in the Southern United States are facing economic hardships as the prices of various forestry products (pulpwood, chip-n-saw, and sawwood) have either gone down or became stagnant (Wear et al. 2007). Consequently, the majority of forest landowners are not undertaking prescribed sustainable forestry practices (like thinning) on their lands. As a result, southern timberlands have accumulated extra biomass in the recent years. This unutilized biomass is vulnerable to pest attack and wildfire (Laughlin 2005). It is feared that a large scale pest attack or wildfire would severely jeopardize the entire economy and environment of the region.

Utilizing extra forest biomass present on region's forestlands for bioenergy development might provide economic incentives to forest landowners by creating a new market for their unutilized biomass. This will also help in meeting the total regional demand of energy in a sustainable manner, as the use of biomass-based energy products is largely carbon neutral. The Table 5-1 gives detail about the forest biomass characteristics, availability, and energy values for southern timberlands (Alavalapati et al. 2009). As deduced from Table 5-1, biomass from the southern forestlands can play a significant role in bioenergy production at the regional level. It might also help in maintaining the ecological integrity of forestlands by reducing the likelihood of pest attacks and wildfires.

Anticipating future potential and positive impacts, several state governments of the region have already announced various incentives to encourage forest biomass-based bioenergy development. For example, in Georgia, three agencies (Georgia Environmental Facilities Authority, Georgia Forestry Commission, and Georgia Department of Economic Development) have been grouped under the umbrella of Georgia's Bioenergy Partnership to promote forest biomass-based bioenergy development. Similarly, in the state of Florida several grants have been made by Florida Energy & Climate Commission to promote biofuel production from forestry feedstocks available within the state.

However, utilization of forest biomass for bioenergy development also raises concerns. For example, it is expected that the bioenergy markets could intensify the current regimes of forest management, leading to severe consequences for biodiversity and soil-moisture conservation (Spangenberg 2008). There are also concerns about the absence of viable commercial technologies for biomass conversion to various energy products (Phillips et al. 2007). Similarly, doubts are raised about the environmental impacts of bioenergy related to land use changes (Searchinger et al. 2008). Furthermore, it is feared that the absence of a specific policy on forest biomass-based bioenergy development at the regional or state level might cause failure of the whole initiative. Already, the consumption of alternative fuels in the southern region is showing a declining trend. For example, the total alternative fuel consumed in southern states was about 98 million gasoline equivalent gallons in 2003 but it fell to about 83 million gasoline equivalent gallons in 2006 (EIA 2006).

Suitable policy environment is needed for sustaining the growth of any sector in the economy. Policy makers always need critical information for formulating effective and enabling policies which can help in integrated development of any sector. An example of critical information is the perceptions of different stakeholder groups associated with cellulosic feedstock-based bioenergy development within the region. Incorporating perceptions of such stakeholder groups is essential for ensuring successful formulation and implementation of any policy (Gregory and Wellman 2001) including a bioenergy policy which focuses on forest biomass-based bioenergy development in the region. Understanding perceptions of such stakeholders will help in identifying those issues which should be addressed in a future bioenergy policy. Addressing such issues will help in reducing conflicts and improving cooperation among different stakeholder groups (Simmons and Lovegrove 2005).

This study uses SWOT-AHP (Strength, Weaknesses, Opportunities, and Threats - Analytical Hierarchical Process) framework to identify differences among perceptions of four bioenergy stakeholder groups (non-governmental organizations [NGOs], government, industry, and academia) regarding forest biomass-based bioenergy development in the Southern United States. The scope of this study is regional, but the findings of the study may be applicable for other regions which are facing similar situations. Moreover, if needed, the same methodology can be replicated in each state to assess perceptions of local stakeholder groups.

This chapter is divided into five sections. The first section introduces the study and provides the rationale for the study. The second section summarizes the literature and identifies existing literature gap. The third section details the SWOT-AHP framework for evaluating stakeholders' perception. The fourth section presents the results; and finally, the fifth section discusses the results and concludes the study.

Literature Review

Kurttila et al. (2000) developed a technique of combining SWOT analysis with AHP. This combination yielded analytically determined priorities for all the factors included in the SWOT analysis and made them commensurable to each other. The authors tested their methodology to assess the feasibility of making a transition from a timber-dominant forest management regime to a certified forest management regime in Finland. They concluded that the SWOT-AHP technique is helpful as making pairwise comparisons forces the decision maker to consider the weights of different factors and to analyze the situation more precisely and in more depth. Masozera et al. (2006) used the SWOT-AHP technique to analyze perception of three stakeholders (communities, a government agency, and an environmental organization) regarding the suitability of a community-based management approach at Nyungwe Forest Reserve in Rwanda. They found that the representatives of local communities perceived that the positive aspects of community-based management outweighed its negative aspects. However, representatives of a government agency and an environmental organization anticipated that weaknesses associated with the community-based management approach outweighed its strengths.

Pesonen et al. (2001a) used the SWOT-AHP technique in connection with strategic planning of natural resource management at the Finnish Forest and Park

Service (FFPS). In this case, SWOT analysis was carried out separately by three business units (Forestry, Recreation, and Nature Protection) at the FFPS and with respect to three dimensions of sustainability (economic, social, and ecological) and for four different strategies (forestry, recreation, protection, and basic). The priorities of the SWOT factors and the suitability of alternate strategies subject to various SWOT factors were estimated by pairwise comparisons. The authors determined that each strategy was consistent with the basic principles of ecological sustainability. In the protection strategy, however, environmental aspects had an especially high priority. Pesonen et al. (2001b) also applied the SWOT-AHP technique to assess the decision of a Finnish forest enterprise to invest in North America. They found that consistency ratios (explained in the next section) were greater than 10% in all the cases except one. The authors concluded that these inconsistencies were due to the presence of a large number of SWOT factors resulting in difficult interpretations of each factor's importance. They recommended that the number of factors within the four SWOT categories should be limited to 10 to ensure consistent responses. It lessens overlapping and user carelessness.

Ananda and Herath (2003) used AHP alone to incorporate stakeholders' preferences into regional forest planning in Australia. They also did a sensitivity analysis to show how the alternatives were prioritized with respect to each objective as well as the overall objective. They concluded that AHP helps the decision-making process to become more transparent by simplifying preference structures and eliminating hidden ambiguities. Rauch (2007) used SWOT analysis to examine strategy formulations in forest owner cooperatives in Austria. The authors concluded that SWOT analysis provides a good overview of the issues and makes it easy to pinpoint important problem areas.

A few studies have analyzed the possible strengths, weaknesses, opportunities, and threats associated with the use of biomass for bioenergy production. Roos et al. (1999) categorized the following factors as critical to bioenergy development—integration with other economic activities, scale effects on bioenergy markets, competition in bioenergy markets, competition with other businesses, national policy, local policy, and local opinion. In another study, Varela et al. (1999) identified several factors under different SWOT categories associated with the use of biomass for electricity production in Spain. For example, they identified the low level of atmospheric emissions compared with other alternatives as strength and the need for a more specialized workforce as weakness. Similarly, the authors categorized topographical limitations as threat and increased energy security as an opportunity. Ulmer et al. (2004) assessed the acceptability of ethanol-blended gasoline in Alabama. They determined that most respondents believed that ethanol produced from biomass is beneficial to the environment and that the reduction in foreign oil dependency was the greatest potential benefit of using ethanol-blended gasoline. Sims (2003) also identified several barriers and opportunities related to bioenergy development. The chances of ecological degradation and land diversion were identified as barriers whereas economic benefits such as rural development were highlighted as opportunities.

The literature review clearly shows two trends. First, no study exists that quantifies stakeholders' perceptions regarding forest biomass-based bioenergy development.

Second, the geographical focus for most of the existing studies is on Europe. It is expected that the present study will help in filling this critical knowledge gap.

SWOT-AHP Framework

SWOT analysis is a strategic management tool that helps to identify internal strengths and weaknesses and external opportunities and threats for any organization, project, or individual (Houben et al. 1999; Dyson 2004). Many applications of SWOT analysis exist in strategic management (Weihrich 1982; Nair and Prasad 2004; Sharma and Bhatia 1996). The combination of a brainstorming session and SWOT analysis with a heterogeneous group of stakeholders constitutes a useful strategy to rank different factors and identify relevant issues (Mollenhorst and deBoer 2004). However, one of the main limitations of SWOT analysis is that the importance of each factor in decision making cannot be measured quantitatively and therefore, it becomes difficult to assess the potential of a factor to influence strategic decisions.

When SWOT analysis is combined with AHP, importance of each factor present in the SWOT categories can be quantified and the effect of a single factor on the overall decision can be assessed (Saaty and Vargas 2001). AHP enables the stakeholders to assign a relative priority to each factor through pairwise comparison. From these pairwise comparisons, the relative priority value of each factor within each SWOT group is computed using the eigen value method as explained below.

Following Shrestha et al. (2004), information derived from the pairwise comparisons can be represented as a reciprocal matrix of weights where the assigned relative weight enters into the matrix as an element a_{ij} and reciprocal of the entry ($1/a_{ij}$) goes to the opposite side of the main diagonal,

$$\mathbf{A} = (a_{ij}) = \begin{pmatrix} w_1/w_1 & w_1/w_2 & \ldots & w_1/w_n \\ w_2/w_1 & w_2/w_2 & \ldots & w_2/w_n \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ w_n/w_1 & w_n/w_2 & \ldots & w_n/w_n \end{pmatrix} \qquad \text{[Eq. 5-1]}$$

where rows indicate ratios of weights of each factor with respect to all others. In the matrix, when i=j, then a_{ij} =1. When we multiply matrix **A** by the transpose of the vector of weights **w**, we get the resulting vector n**w**,

$$\mathbf{Aw} = n\mathbf{w} \qquad \text{[Eq. 5-2]}$$

where **w** = $(w_1,w_2,\ldots,w_n)^T$ and n is the number of rows or columns. The above equation can also be written as:

$$(\mathbf{A}-n\mathbf{I})\ \mathbf{w} = 0 \qquad \text{[Eq. 5-3]}$$

where n is also the largest eigen value, $\boldsymbol{\lambda}_{max}$, or trace of matrix **A** and **I** is the identity matrix of size n. Saaty (1977) demonstrated that $\boldsymbol{\lambda}_{max}$ = n is a necessary and sufficient condition for consistency. Inconsistency may arise when $\boldsymbol{\lambda}_{max}$ deviates from n due to varying responses in the pairwise comparisons. Therefore, the matrix **A** should be tested for consistency using the formula,

$$\mathbf{CI} = (\boldsymbol{\lambda}_{max} - n)/(n-1) \qquad \text{[Eq. 5-4]}$$

$$\mathbf{CR} = \mathbf{CI}/\mathbf{RI} \qquad \text{[Eq. 5-5]}$$

where **CI** is the consistency index, **RI** is a random index generated for a random matrix of order n, and **CR** is the consistency ratio (Saaty 1993; Mawapanga and Debertin 1996). The general rule is that **CR** should be≤ 0.1 (10%) for the matrix to be consistent. Homogeneity of factors within each group, a smaller number of factors in each group, and a better understanding of the decision problem improves the **CI**. SWOT-AHP analysis can be conducted even with a small sample of individuals or groups who are knowledgeable of the issue under investigation. In this way, SWOT-AHP differs from other statistical analyses which require large samples to derive confidence intervals around the means and draw inferences for a relevant population.

Methods

A contact list of professionals working on different aspects of bioenergy development in the Southern United States was prepared. This list was based on personal contacts, publications, projects awarded by different government and private agencies, state government agencies with a focus on bioenergy development, feedback from previously identified stakeholders, and comprehensive internet search. To identify the factors in each SWOT category, an open-ended online questionnaire was administered to all the identified stakeholders. Questionnaire was electronically sent to 258 experts in 14 southern states and responses from 37 experts were obtained. Responses were analyzed and suitable factors under each SWOT category were extracted (Table 5-2).

Based on the factors identified in each SWOT category, a second questionnaire was prepared. A brief explanation of each factor was included in the questionnaire to ensure a common understanding among the respondents. This questionnaire contained pairwise comparisons of each factor in a particular SWOT category against all other factors in the same category. The respondents were asked to evaluate both the factors present in a pairwise comparison and then mark the order of importance of one factor over another based on their own understanding. For example, in the pairwise comparison of *promotes energy security* vs. *reduces greenhouse gas emissions* under SWOT category of strength, the respondent would first decide which factor is more important and then assign a weight ranging from one to seven (1, 3, 5, and 7) indicating the relative magnitude of its importance against another factor. The data from pairwise comparisons were used to estimate a priority value for each factor within each SWOT category. Figure 5-1 represents a section of the used questionnaire. While administrating the questionnaire, the numbers were replaced by more familiar scale of comparison (1= “Equal”, 3 = “Moderate”, 5 = “Strong”, and 7 = “Very Strong”) to facilitate respondents. This was done based on the findings of a focus group discussion in which participants suggested to reduce the number of comparison scales from five to four and use more familiar comparison scales (in words) rather than numbers.

The questionnaire was administered on August 5, 2008 at the Southern Bioenergy Roadmap Stakeholder Meeting convened by the Southeast Agriculture & Forestry Energy Resources Alliance at Memphis, Tennessee. Respondents were classified into four stakeholder groups namely NGOs, government, industry, and academia. Individual responses in each stakeholder group were combined to obtain the geometric mean for that group (Saaty 2001). The number of complete responses for NGOs, government, industry, and academia stakeholder groups were 7, 8, 10, and 10 respectively. The combined responses for each stakeholder group were analyzed using the SWOT-AHP technique. The factor with the highest priority score was identified in each SWOT category and for each stakeholder group. Separate questionnaires for each stakeholder group containing pairwise comparisons between the factors that got highest priority scores in each SWOT category were developed. This was done to estimate the overall priority of different factors with respect to each other. These questionnaires were administered at the Biomass South 2008 Conference on September 21, 2008 at Raleigh, North Carolina. Stakeholder group-specific questionnaires were also sent electronically to the participants of the previous conference. The number of complete responses for NGOs, government, industry, and academia stakeholder groups were 6, 5, 7, and 7 respectively. Responses were analyzed using the aforementioned procedure, and the final priority rankings for the factors under each SWOT category for all stakeholder groups were obtained.

Results

A summary of the factors and their overall priority scores is shown in Table 5-3. Factors with the highest priority score for each SWOT category in a particular stakeholder group are highlighted in bold and the highest overall priority score is also highlighted. For all comparisons, the CR was always less than 0.1. Following Masozera et al. (2006), the scores of strength and opportunity factors can be interpreted as positives while the scores of weakness and threat factors as negatives for the forest biomass-based bioenergy development in the Southern United States. For example, the overall priority scores for strength and opportunities were 0.4643 and 0.3132 for academia stakeholder group. The sum of priority scores was 0.7775 implying that about 78% of the overall perception about the use of forest biomass for bioenergy development is positive for the academic stakeholder group. The overall priority score of other stakeholder group can be interpreted in the same manner. The relative importance of each factor within each SWOT category provides valuable insight for decision-making. For example, a priority value of 0.2663 for *promotes energy security* for academic stakeholder group indicates that this factor accounts for about 27% of overall strength. The overall perception of each stakeholder group is discussed in detail below.

NGOs: The overall perception of NGO stakeholder group regarding the use of forest biomass for bioenergy development in the Southern United States was mostly determined by opportunities (40%). In particular, NGOs preferred two factors within the opportunity category i.e., *rural development* (37%) and *presence of government support/commitment* (20%). These two factors explained 57% of NGO's perception regarding opportunities (Figure 5-2). Weaknesses were the second most significant in determining overall perception (27%). The two factors which got highest priorities within the weakness category were *the conversion technologies are still under trial* (30%) and *the uncertain future of bioenergy markets* (26%). Strengths were the third most significant determinant (20%). This stakeholder group gave the highest priority under the strength category to *sufficient forest biomass availability* (34%) followed by *promotes energy security* (29%). Threats were not given much importance by this stakeholder group as threats explained only 13% of the overall perception. In the threat category, the highest priority was given to *competes with conventional forest products industry* (25%) followed by *possible damages to forest ecology* (23%).

Government: The strengths were the significant determinants of government representatives' overall perception (37%). The two strength factors namely *less or no competition with food production* (28%) and *promotes energy security* (27%) were given highest rankings. The remaining SWOT categories i.e., weaknesses, opportunities, and threats were given almost equal weights by government representatives i.e., 20%, 24%, and 19%, respectively (Figure 5-3). The highest priority factors within the weakness category were *conversion technologies are still under trial* (30%) and *still not competitive with coal, gasoline, and corn-based ethanol* (25%). Similarly, *emerging* *future carbon markets* (26%) and *rural development* (24%) got highest priorities under the opportunities category. Among threats, the highest priorities were given to *competes with conventional forest product industry* (24%) and *cheap imports from other countries* (21%).

Industry: Strengths (35%) and weaknesses (32%) dominated the overall perception of the industry stakeholder group (Figure 5-4). The *promotes energy security* (35%) was the highest priority factor in the strength category while the highest priority was given to *conversion technologies are still under trial* under the weakness category (43%). Opportunities determined 24% of overall perception. The two highest priorities were given to *rural development* (27%) and *presence of government support/commitment* (26%) under opportunities category. Threats explained only 9% of the total perception associated with the forest biomass-based bioenergy development. Two factors namely *competes with conventional forest product products industry* (26%) and *cheap imports from other countries* (21%) were emphasized within the category of threats.

Academia: The strengths category was the most significant determinant of the overall perception (46%). Interestingly, all factors in the strength category were prioritized nearly equally (Figure 5-5) with the highest weight given to *promotes energy security* (27%). After strengths the next highlighted category was opportunities (31%). The highest priorities in this category were *rural development* (33%) and *presence of government support/commitment* (24%). Both weaknesses (10%) and threats (12%) contributed marginally towards the overall perception. The *conversion technologies are still under trial* (34%) and *still not competitive with coal, gasoline, and corn-based* *ethanol* (26%) were the highest weakness factors. Among threats, *competition from other renewable energy sources* (28%) and *possible damages to forest ecology* (27%) were given highest priorities.

The results of this study indicate that all four stakeholder groups are in favor of promoting forest biomass-based bioenergy development in the Southern United States. Results of the study are consistent with the other studies which have tried to evaluate public preferences for green energy. For example, Borchers et al. (2007) used choice models to evaluate willingness-to-pay for voluntary participation in green electricity program. They found a positive willingness-to-pay for green electricity market. Roe et al. (2001) using hedonic analysis concluded that green electricity is an important indicator of price premium charged by companies.

Discussions

On an average, the overall perception for all stakeholder groups was determined by strengths (35%) and opportunities (30%) followed by weaknesses (22%) and threats (13%). Three strength factors were given the highest preference by all stakeholder groups: *promotes energy security*, *sufficient forest biomass availability*, and *less or no competition with food production*. It was noted that the factor *reduces greenhouse gas emissions* was not a high priority factor for any stakeholder group. Among weaknesses, all four stakeholder groups gave their highest priority to the *conversion technologies are still under trial*. All stakeholder groups except government gave the highest priority to *rural development* under the opportunities category. Government representatives gave highest priority to *emerging future carbon markets* under the same SWOT category. As future carbon markets might provide incentives to both forest biomass producers and industries, carbon markets are expected to give an impetus to forest biomass-based bioenergy development. However, deliberations on this issue are still at the policy level; therefore, the preference of government officials for the opportunities provided by future carbon markets seems to be logical. The two threats which got the highest priorities scores were *competition from other renewable energy sources* and *competes with conventional forest product industry*. However*, possible damages to forest ecology* was not a significant determinant of the stakeholders' perceptions regarding threats. In the Southern United States, almost every state government has its own best management practices for forestry. These practices are stringent regarding the use of chemicals for maintaining proper water quality and the forest landowners' compliance with these practices is monitored regularly (Adams 1998). Thus, this factor might have assured all the stakeholder groups that utilizing forest biomass for bioenergy development will not have negative consequences for forest ecology. Another possibility is that the stakeholders were aware of the accumulated biomass in regional forestlands and the hazard that it presents to the forest ecology and local economy. As such, utilization of forest biomass for bioenergy production was thought to be an appropriate step.

All the stakeholder groups recognized *government support* as one among their top preferences within opportunity category, therefore it can be inferred that in the near future bioenergy policy should provide government support for promoting forest biomass-based bioenergy development in the region. This becomes even more critical when markets are evolving and are at nascent stage. Similarly, there also exists a need to address impact of the whole initiative on the other sectors of economy especially those sectors which use forest biomass as feedstock like pulp and paper mills. Any future bioenergy policy should define all the sectors clearly for preventing feedstock overlaps. It was also found that all stakeholder groups were particularly concerned about the *unavailability of commercial scale conversion technology*. It is expected that successful demonstration of existing or future conversion technologies at a commercial scale will spur growth in forest biomass-based bioenergy production on its own.

Conclusions

This study uses SWOT-AHP approach to assess the perceptions of four stakeholder groups regarding forest biomass-based bioenergy development in the Southern United States. The region was selected due to the existence of a large forestry base, the potential role that the region will play in meeting the future national demand for cellulosic biomass, the rising energy needs of the region, and the emphasis of various state governments on promoting cellulosic biomass as a sustainable energy source.

It can be concluded that all the stakeholder groups have recognized that the Southern United States has a great potential of forest biomass-based bioenergy development. Therefore, there exists a need to design a suitable policy which can promote such a development in the region by incorporating issues deemed important by various stakeholder groups.

It is however to be kept in mind that the results represent aggregated opinions of respondents belonging to one out of four stakeholder groups. Though the CRs were found consistent for each stakeholder group in this study, the author still feels that there exists a need for incorporating more stakeholder groups (forest landowners, consumers) to obtain a more clear understanding of perceptions for effective policy formulation.

Table 5-1. Forest biomass availability and energy values from southern timberlands

State	Timberland Area (*million acres*)	Live Biomass (*million dry tons*)	Roundwood Production (*million* ft^3)	Timber Removals (*million* ft^3)	Logging Residues (*million* ft^3)	Net Annual Growth (*million* ft^3)	Energy Value *(Billion Btu)*
Alabama	22.6	882.4	1,119.1	1,157.3	254.7	1,512.5	181,500
Arkansas	18.5	761.6	707.3	810.3	184.7	1,027.8	123,336
Florida	16.7	529.0	529.9	574.5	119.2	735.0	88,200
Georgia	24.9	1,032.7	1,203.3	1,340.5	329.1	1,927.6	231,312
Kentucky	12.1	621.2	206.1	296.3	107.4	469.8	56,376
Louisiana	14.1	594.7	741.2	857.9	276.1	832.7	99,924
Mississippi	15.1	590.1	165.7	1,093.9	89.0	1,247.2	149,664
Missouri	19.6	812.6	937.3	187.2	326.8	438.5	52,620
North Carolina	18.6	935.4	858.5	1,075.0	211.6	1,458.6	175,032
Oklahoma	5.4	155.4	334.8	138.5	95.7	243.3	29,196
South Carolina	12.9	573.5	601.8	671.5	151.4	1,037.3	124,476
Tennessee	14.0	726.7	338.9	377.5	67.7	801.2	96,144
Virginia	15.7	859.6	534.9	644.3	155.0	956.8	114,816
West Virginia	12.0	820.1	163.7	158.4	100.7	436.3	52,356
Region Total	222.2	9,895.2	8,442.4	10,041.9	2,469.0	13,124.6	1,574,952

Table 5-2. Relevant factors identified in each SWOT category

	Strengths		Weaknesses
S1	Promotes Energy security	W1	Conversion technologies are still under trial
S2	Reduces greenhouse gas emissions	W2	Uncertainties related to forest biomass production
S3	Less or no competition with food production	W3	Still not competitive with coal, gasoline and corn based ethanol
S4	Sufficient forest biomass availability	W4	Uncertain future of bioenergy markets
	Opportunities		Threats
O1	Emerging future carbon markets	T1	Competes with conventional forest products industry
O2	Presence of government support/commitment	T2	Competition from other renewable energy sources
O3	Favorable public opinion	T3	Possible damages to forest ecology
O4	Improves the sustainability of forests	T4	Reduction in prices of fossil based energy resources
O5	Rural development	T5	Cheap imports from other countries

Table 5-3. Summary of the priority scores of all SWOT factors and categories

SWOT Categories	Factor Priority				Overall Priority			
	Academia	Government	NGO	Industry	Academia	Government	NGO	Industry
Strengths					**0.4643**	**0.3671**	**0.1991**	**0.3486**
S1	0.**2663**	0.2704	0.2906	**0.3552**	0.1236	0.0993	0.0579	0.1238
S2	0.2475	0.2227	0.1292	0.1891	0.1149	0.0817	0.0257	0.0659
S3	0.2461	**0.2857**	0.2356	0.2116	0.1143	0.1049	0.0469	0.0737
S4	0.2401	0.2212	**0.3446**	0.2441	0.1115	0.0812	0.0686	0.0851
Weakness					**0.1047**	**0.2003**	**0.2745**	**0.3196**
W1	0.**3423**	**0.2974**	**0.3036**	**0.4338**	0.0359	0.0596	0.0833	0.1386
W2	0.2350	0.2474	0.1917	0.1818	0.0246	0.0496	0.0526	0.0581
W3	0.2575	0.2563	0.2393	0.1958	0.0270	0.0513	0.0657	0.0626
W4	0.1653	0.1989	0.2654	0.1886	0.0173	0.0398	0.0728	0.0603
Opportunities					**0.3132**	**0.2388**	**0.3976**	**0.2423**
O1	0.0981	**0.2612**	0.1618	0.1009	0.0307	0.0624	0.0643	0.0245
O2	0.2387	0.1829	0.2004	0.2660	0.0748	0.0437	0.0797	0.0645
O3	0.1459	0.1542	0.1344	0.1770	0.0457	0.0368	0.0534	0.0429
O4	0.1897	0.1595	0.1295	0.1882	0.0594	0.0381	0.0515	0.0456
O5	**0.3276**	0.2422	**0.3740**	**0.2679**	0.1026	0.0578	0.1487	0.0649
Threats					**0.1178**	**0.1939**	**0.1289**	**0.0895**
T1	0.1552	**0.2427**	**0.2535**	**0.2574**	0.0183	0.0471	0.0327	0.0230
T2	**0.2831**	0.1675	0.1335	0.1676	0.0333	0.0325	0.0172	0.0150
T3	0.2667	0.1837	0.2357	0.1742	0.0314	0.0356	0.0304	0.0156
T4	0.1423	0.1971	0.2199	0.1881	0.0168	0.0382	0.0283	0.0168
T5	0.1528	0.2089	0.1574	0.2128	0.0180	0.0405	0.0203	0.0190

S1: Promotes energy Security; S2: Reduces greenhouse gases emissions;S3: Less or no competition with food production;S4: Sufficient forest biomass availability;W1: Conversion technologies are still under trial;W2: Uncertainties related to forest biomass production;W3: Still not competitive with coal, gasoline and corn based ethanol; W4: Uncertain future of bioenergy markets;O1: Emerging future carbon markets;O2: Presence of government support/commitment; O3: Favorable public opinion;O4: Improves the sustainability of forests;O5: Rural development; T1: Competes with conventional forest products industry;T2: Competition from other renewable energy sources;T3: Possible damages to forest ecology;T4: Reduction in prices of fossil based energy resources;T5: Cheap imports from other countries

Please compare given factors with each another one by one and tick mark the appropriate column.
Please mark one response per comparison.

	STRENGTH CATEGORY							
	← MORE →			Comparison Levels			← MORE →	
Factors	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Factors
Promotes energy security								Reduces greenhouse gas emissions
Promotes energy security								Less or no competition with food
Promotes energy security								Sufficient forest biomass availability
Reduces greenhouse gas emissions								Less or no competition with food
Reduces greenhouse gas emissions								Sufficient forest biomass availability
Less or no competition with food production								Sufficient forest biomass availability

Figure 5-1. Pairwise comparison of factors under strength category

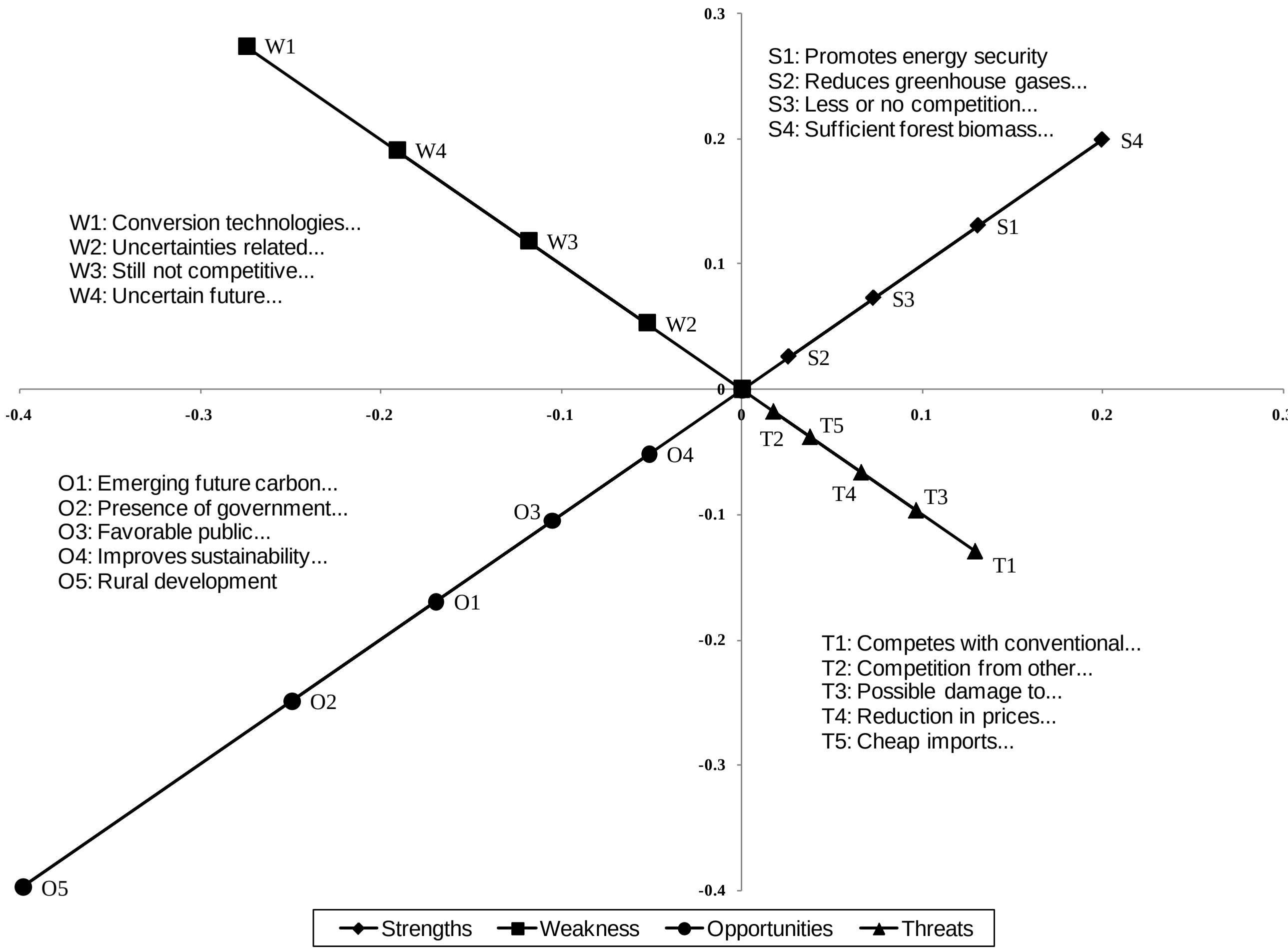

Figure 5-2. Perception map of the NGO stakeholder group

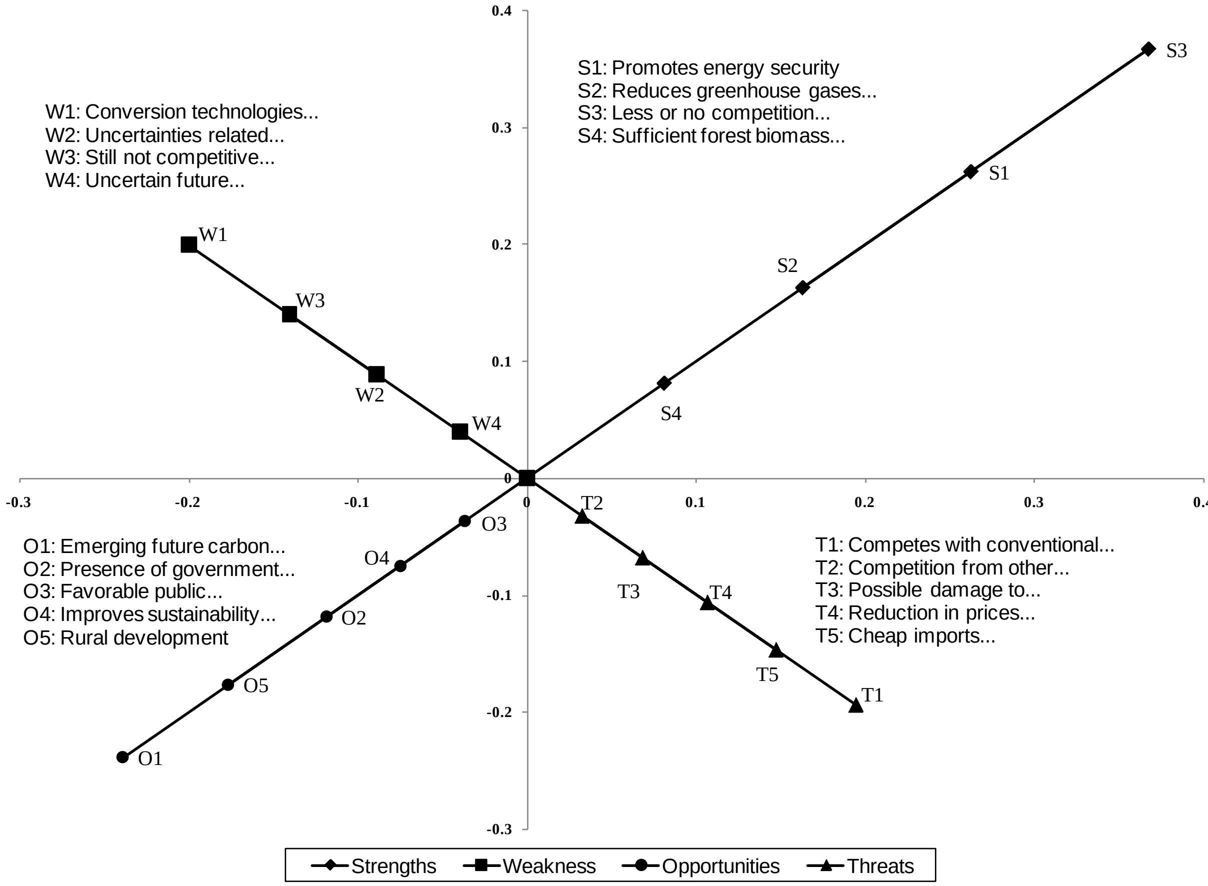

Figure 5-3. Perception map of the government stakeholder group

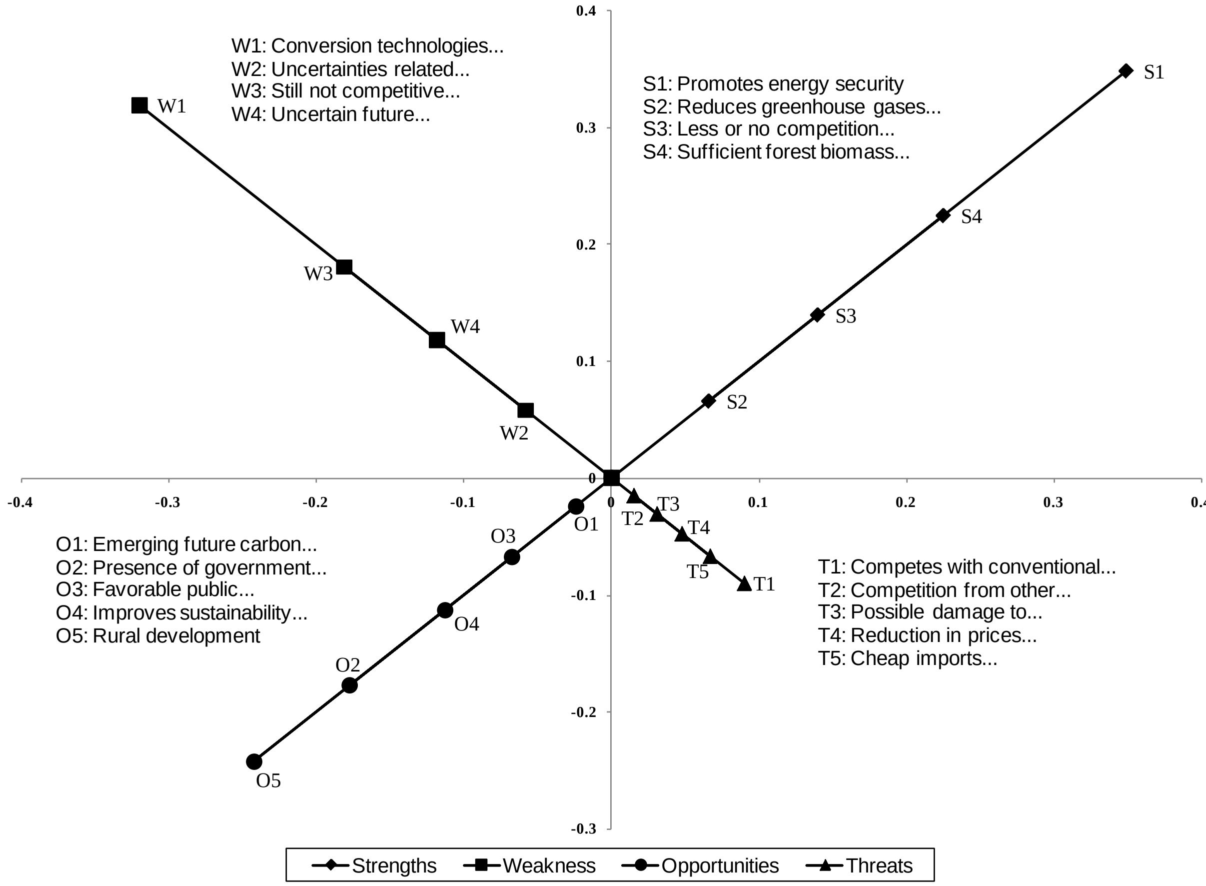

Figure 5-4. Perception map of the industry stakeholder group

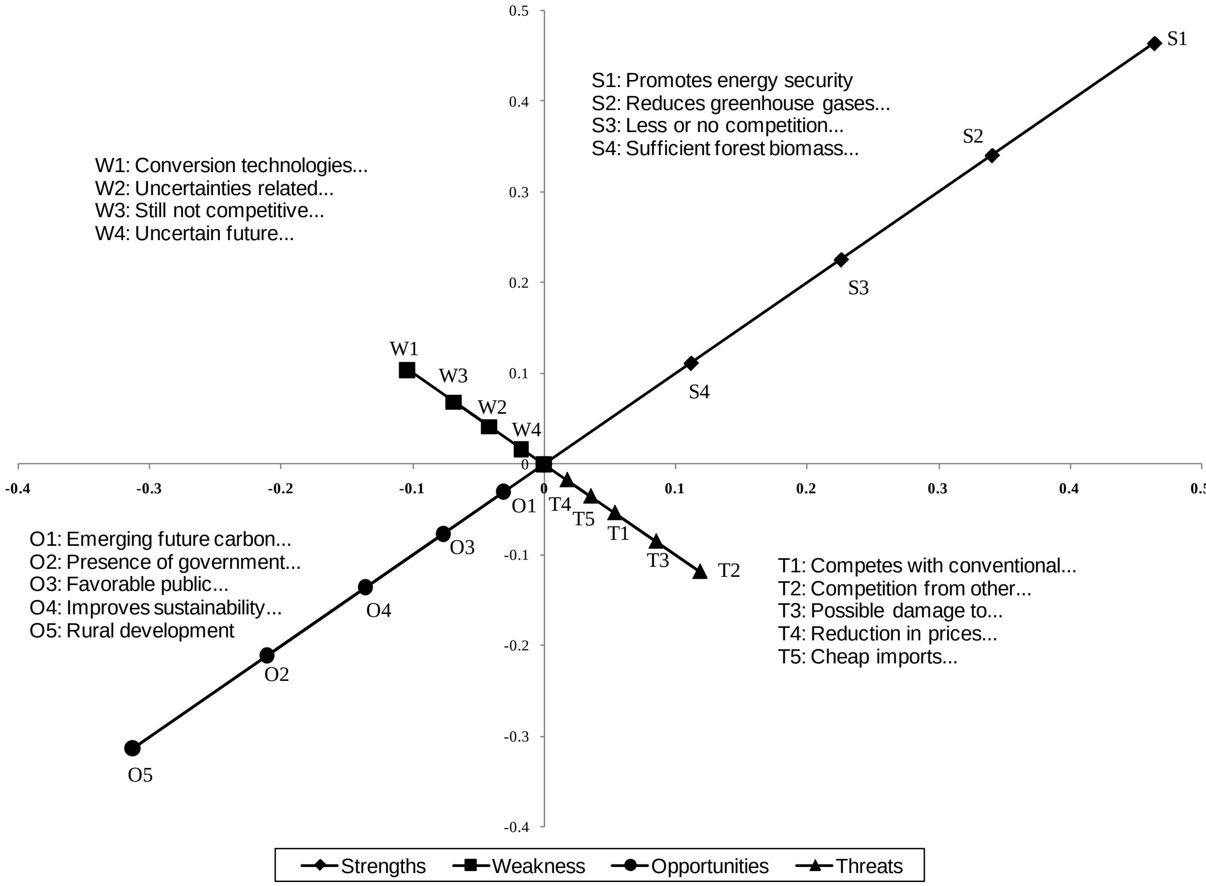

Figure 5-5. Perception map of the academia stakeholder group

CHAPTER 6
SUMMARY AND CONCLUSIONS

Introduction

Forest biomass available on Non-Industrial Private Forest (NIPF) lands located in the Southern United States can play an important role in meeting the scheduled production target of cellulosic ethanol at the national level. Therefore, this study took a holistic approach in analyzing various issues related to the whole initiative of producing cellulosic ethanol from forest biomass.

Specifically, the present status of existing conversion technologies was reviewed and their performance in terms of unit production cost of ethanol and adoption was ascertained. An attempt was also made to capture the future trajectory of technology development. Next, the percentage reduction in greenhouse gas emission was ascertained for ethanol produced from slash pine biomass. The net energy ratio for the ethanol produced at the mill was also calculated. Suitable comparisons of calculated net energy ratio and net reduction in global warming were made with cellulosic and agricultural feedstocks. Next, the impact of emerging voluntary carbon and bioenergy markets on the profitability of NIPF landowners was ascertained. A case study approach was adopted and an acre of slash pine plantation was selected as a representative species. The changes in land expectation value and optimal rotation age were recorded for several scenarios of carbon and logging residue payments. This was followed by a study which captured perceptions of four different stakeholder groups about the use of forest biomass-based bioenergy development in the Southern region using SWOT-AHP technique.

It is expected that the results of this study would enhance our understanding about the utilization of forest biomass for cellulosic ethanol production and help in achieving the goals of energy independence and reduction in greenhouse gas emissions.

Policy Implications

The findings of the first chapter clearly reveal that policy makers are interested in promoting use of cellulosic feedstocks for ethanol production. Several acts have been passed in recent years which attempt to facilitate production of cellulosic ethanol in the country. It can be deduced that subsidies, grants, and other incentives provided to corporations and research organizations would help in overcoming initial challenges related with cellulosic ethanol production in the country.

The findings of the second chapter suggest that no commercially viable conversion technology exists for cellulosic ethanol production in the country. Therefore, a need exists to develop a suitable conversion technology through which cost of cellulosic ethanol production becomes comparable to the ethanol obtained from corn. Both public and private sectors are investing a lot in the technology development and it can be expected that such a technology will be developed in coming years. In addition to conversion technology, research is also needed to reduce the transportation cost of the feedstock so that the production cost of the ethanol can be reduced further. It is also expected that the future technology will be based on an integrated industrial framework in which cellulosic ethanol will be a byproduct of a main product. For example, an integrated paper mill can produce ethanol from the waste generated during the paper manufacturing process. Additionally, more feedstocks need to be tested for accessing their feasibility in ethanol production. This will help in reducing risks associated with crop failure in case of a natural calamity.

The focus of policy makers should also be on developing suitable guidelines for forest management to ensure integrated development of the region. This becomes especially true when it is expected that the use of forest biomass for bioenergy development might affect existing forest industry of the region. Also, it might be possible that intensive management of forestlands for producing required biomass for emerging bioenergy market could lead to several ecological problems like soil degradation, water quality deterioration, etc. In absence of such guidelines, the emerging bioenergy market in the region can cause adverse impacts on the local economy and ecology.

The findings of the third chapter suggest that production of ethanol from the biomass obtained from an intensively managed forestland will help in reducing emissions of greenhouse gases. Findings suggest that the ethanol produced from forest biomass has a high energy ratio when compared to other feedstocks. These findings imply that the ethanol production from forest biomass is environmental friendly. However, special precautions are needed to capture methane emissions at the mill otherwise the ethanol production from forest biomass will not be able to serve the intended objective of reduction in greenhouse gas emissions.[1] This implies that policy makers should emphasize capturing emissions at the mill by making suitable provisions in existing pollution and environmental laws. Additionally, the cost of ethanol production from slash pine biomass and using the two-stage dilute sulfuric acid conversion technology was found to be higher than the cost of ethanol produced from corn. This suggests that more efforts are needed to further reduce the production cost of ethanol. Reducing the cost of biomass feedstocks by increasing the energy density and

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[1] When compared with equivalent amount of carbon dioxide, the global warming impact of methane is about 23 times more than carbon dioxide.

improving the hydrolysis efficiency can significantly help in reducing the production cost of cellulosic ethanol.

The findings of the fourth chapter indicate that emerging voluntary carbon and bioenergy markets will help in increasing the profitability of NIPF landowners to a great extent without any noticeable change in forest rotation age. This implies that NIPF landowners will be interested in producing biomass for emerging bioenergy markets even in the presence of voluntary carbon markets.

The findings of the fifth chapter suggest that all the major stakeholders are in favor of forest biomass-based bioenergy development in the Southern region. For example, all stakeholder groups agreed that use of forest biomass for bioenergy development will promote energy security and sufficient forest biomass is available which can be utilized to produce bioenergy. However, it would be critical to address the weaknesses and threats perceived by these stakeholders in order to scale up forest bioenergy markets in the region.

Limitations of the Study

Although the present study attempted to be relatively comprehensive while analyzing various issues related to the use of forest biomass for bioenergy development in the Southern region of the United States, many limitations of the study remain.

In the second chapter of the study, more specific details of some emerging conversion technologies (e.g., biomass fractionation) were not found. Similarly, feedstock details for some upcoming cellulosic ethanol mill were unavailable in an objective manner. In some cases, the conversion technology that will be employed for producing cellulosic ethanol was also not explicitly mentioned.

In the third chapter, the global warming impact of cellulosic ethanol produced from slash pine biomass was ascertained. The system boundary included all the steps starting from seed orchard management to the point where produced E85 fuel is consumed in an automobile. For many intermediate steps, the values of energy and material use were approximated by interviewing managers. This might have an effect on obtained results due to presence of subjectivity in responses. Additionally, other impacts like eco-toxicity, eutrophication, etc. were not ascertained in the study. Similarly, production cost of the ethanol does not include any non-market values associated with the existence or aesthetics of the forest. It only includes those values which were representative of prevailing conditions of Southern pine plantation at the time of study. Production cost is not the only economic factor to consider. Impacts of government incentives such as tax rebates and subsidies should also be evaluated in order to make a fair comparison of economic viability.

In the fourth chapter, the carbon model used for assessing soil carbon was parameterized by importing parameters from European studies, as several parameters values were not available for the Southern United States. Similarly, the real price of registering carbon credits at the Chicago Climate Exchange (CCX) was not available. Apart from that, the values of emissions at the time of harvesting and thinning were approximated based on interviews with forest landowners and loggers. This raises small concerns about the validity of calculated emission values.

In the fifth chapter, perceptions of only four stakeholder groups (industry, academia, government, and non-governmental organizations) have been analyzed. More number of stakeholder groups should have been included to ascertain their perceptions like forest landowners. This would have given more credibility to the overall findings.

Future Research

It is expected that the production of cellulosic ethanol from forest biomass will have an impact on the existing land cover in the Southern region. Similarly, the emergence of forest biomass-based bioenergy industry will have an impact on the existing forest industry, as both these industries will compete for the same biomass to meet their demand. This study does not quantify these impacts and it is expected that future research work will focus on the same. Additionally, no risk was considered while evaluating the economic impact of emerging voluntary carbon and bioenergy markets on an NIPF landowner. Assessing impact of risk on the profitability of landowners is essential, as this determines the willingness of a landowner about participating in bioenergy markets. In case of high risk and low profitability, a landowner can select an alternate but more profitable land use. This might severely affect the whole premise of forest biomass-based bioenergy development in the Southern region. Furthermore, no correlation among SWOT categories was assumed in this study. It might be possible that there exists a strong correlation among various factors present in different SWOT categories. Therefore, the obtained values are not true values. In the future research, a new technique of analytical network process can be used to ascertain the correlation among different SWOT categories for deriving the priorities of different factors.

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BIOGRAPHICAL SKETCH

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