ECONOMIC AND ENVIRONMENTAL IMPACTS OF ETHANOL PRODUCTION FROM SOUTHERN UNITED STATES SLASH PINE (*Pinus elliottii*) PLANTATIONS

By

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A THESIS PRESENTED TO THE GRADUATE SCHOOL
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To my family.

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LIST OF ABBREVIATIONS

BCR	Benefit Cost Ratio
CBA	Cost Benefit Analysis
CDM	Clean Development Mechanism
CCX	Chicago Climate Exchange
EIA	Energy Information Administration
EISA	Energy Independence and Security Act
GHG	Greenhouse Gas
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IRR	Internal Rate of Return
ISO	International Organization for Standardization
LCA	Life Cycle Analysis
LCI	Life Cycle Inventory
LCIA	Life Cycle Inventory Analysis
LEV	Land Expectation Value
NEB	Net Energy Balance
NIPF	Non-Industrial Private Forest
NPV	Net Present Value
NTFP	Nontimber Forest Product
TRACI	Tool for the Reduction and Assessment of Chemical and other environmental Impacts
UNFCCC	United Nations Framework Convention on Climate Change
USDA	United States Department of Agriculture
USDOE	United States Department of Energy
VEETC	Volumetric Ethanol Excise Tax Credit

Abstract of Thesis Presented to the Graduate School
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Chair: Janaki R.R. Alavalapati
Co-chair: Marian Marinescu
Major: Forest Resources and Conservation

Increased energy consumption at the global and national levels in addition to concerns over supply security of current energy sources has contributed towards increased research and development of alternative energy sources. Biomass in particular has become a focus of the public and policy makers in the United States. The growing interest in biofuels coupled with the challenges of limited markets for small diameter wood and overstocked forests facing non-industrial private forest (NIPF) owners of the U.S. South present a unique opportunity to utilized small diameter biomass from these lands as a feedstock for biofuel production. Slash pine (*Pinus elliottii*) plantations are studied in this thesis as a feedstock for ethanol production. Specifically this study addresses the profitability to the NIPF owner in the face of increased demand for biofuel feedstock, the unit cost of production of cellulosic ethanol from NIPF biomass feedstock, the net energy balance (NEB) of ethanol produced from Southern NIPF biomass, the environmental impacts associated with the life cycle of the ethanol production process, and the potential supply of ethanol from the region. The profitability to forest landowners is shown to be enhanced by incorporating the biofuel market. Land values are shown to rise by $200 per acre through incorporating the sale of biomass for ethanol production. The unit cost of production is

calculated to be $0.56 per liter for a 50 million gallon per year output and a life span of 15 years. The net energy balance was calculated to be 5.67 units of energy produced for every unit of energy put into the system. The total feedstock available suggests that up to 5.5 billion gallons of ethanol, equivalent to 4% of U.S. annual gasoline use can be produced per year from small diameter pulpwood and harvest residues. The overall analysis indicates that ethanol production from Southern pine plantations offers a promising option for biofuel production.

CHAPTER 1
INTRODUCTION

Energy Production and Consumption Trends

The technological advances achieved during the industrial revolution of the 19^{th} century allowed an exponential increase in the production of transportation, manufacturing, and consumer goods. This increase has enhanced the potential for mobility, food production, healthcare, access to information, and a myriad of other beneficial contributions towards the quality of life of many of the planet's people, particularly in developed nations. These technologies have also increased demand for the energy rich fossil fuels of oil, coal, and natural gas, once thought to be limitless and which are used for the development and implementation of so many of today's technologies. As a result, total global primary energy consumption increased from 283.5 to 462.8 quadrillion BTU's between 1980 and 2005, an increase of 63%, as illustrated in Figure 1-1 (EIA 2007). Over the past 30 years, petroleum, natural gas, and coal consumption have represented between 85 and 90% of total global primary energy consumption, representing 86% today (EIA 2007). Figure 1-2 shows the total energy consumption for the U.S. by source for the year 2004. Recently, however, several concerns have arisen over the continued utilization of these fuels. These concerns span a wide spectrum including economic issues of supply and demand, social and political issues of energy security, and a wide range of environmental and health impacts stemming from increased smog formation, acid rain, and global climate change.

Economics

The economic concerns of our current energy supply stem largely from the limited nature of these fuel sources as nonrenewable resources, meaning that these fuels cannot be regenerated on a scale comparable with their consumption. Additionally, these fuels are being consumed ever more rapidly due to the increased number of global consumers and to the increased consumption per capita. Ironically, these fuels provide the power source for the continued technological development and expansion throughout the world that allows for extended life spans and increased population growth, which place further demands on our current energy sources. Specifically, the availability of petroleum has become a primary economic concern for much of the world. This concern has been highlighted recently by the record surges in the cost of oil. The price of a barrel of crude oil on June 26, 1998 was $10.83. On June 27, 2008 the price was $131.41, representing an 1113% increase over the ten year period, as demonstrated by the steep upward slope in Figure 1-3 (EIA 2008).

For oil importing nations, this price increase has a significant impact on the trade balance. For example, the U.S. imported over 3.5 billion barrels of crude oil in 2007 (EIA 2008). As demonstrated by Figure 1-4, U.S. energy consumption has continued to increase, while production has flattened out. This leads to an increase in imports in order to meet demand, which negatively impacts the U.S. balance of trade. According to the Federal Reserve Bank of San Francisco, the higher cost of petroleum imports have accounted for over 50% of the decline in the overall trade deficit from January 2002 to July 2006 (Cavallo 2006). It is further projected that oil prices will remain at their currently high levels into the future, which will require a contraction of domestic use within the U.S. in order to return the balance of trade to its baseline level (Rebucci and Spatafora 2006). Economic concerns such as these further contribute towards the increasing interest in alternative energy sources.

Socio-Political

The concerns brought on by the limited nature of our current fuel sources have been worsened by the concentration of these sources in regions troubled by geopolitical struggle. In particular, the reserves of oil in the Middle East have become a sensitive topic due to the ongoing military and political struggles within Iraq and other Middle Eastern nations, which produce a majority of the global crude oil output. As a result the continued dependence of society, and the U.S. in particular, on Middle Eastern oil has generated many concerns over the security of the energy supply and, in turn, the nation itself.

Environmental Impacts

In addition to the economic and political concerns highlighted above, the environmental consequences of fossil fuel use have come to be viewed as a major issue in light of the findings of the Intergovernmental Panel on Climate Change (IPCC) regarding the linkage of greenhouse gas (GHG) emissions with global warming and associated climate change (IPCC 2007). Additionally, other environmental impacts linked with fossil fuel use have previously been established regarding acid rain, such as in the 'Black Triangle' of Europe and the North American Great Lakes region, smog formation in major cities such as Los Angeles and Mexico City, and their resultant detrimental influences on human health in the form of asthma, respiratory illness, and cancer (Kovats 2003). Although the modeling intricacies of the magnitude of impacts associated with global climate change remain to be firmly established in consensus, it is clear that there is a fundamental link between the emissions of GHGs (primarily carbon dioxide from oil and coal combustion) into the atmosphere and the continued destabilization of the planet's climate, which may lead to any number of endpoint impacts including sea level rise, desertification, increased storm intensity, and shifts in ecosystem functioning (NAST 2000).

Alternatives to Fossil Fuels

Based on the three categories of concerns described above, there is ongoing research and development of a myriad of alternative energy sources to fossil fuels aimed at alleviating and mitigating said concerns (Hill *et al.* 2006, Tilman *et al.* 2006). Of these alternatives, there is a wide range of distribution across the status of theoretical understanding, feasibility, and commercialization. The major alternatives currently being discussed are nuclear energy, hydrogen fuel cells, solar power, wind, hydroelectricity, geothermal, and biomass, each of which are briefly presented here.

Nuclear. Electricity generated through nuclear energy is a proven technology that is currently used in many developed countries and supplies about 20% of the electricity demand in the U.S. (DOE 2008). Some of the benefits of nuclear energy include that it is viewed as a potentially carbon neutral energy source, helping to alleviate concerns over GHG emissions. This type of energy is capable of producing vast quantities of usable energy and still has room for improvement in efficiency of conversion. However, several hurdles remain in its path to more widespread use including the problem of disposing the radioactive waste produced as a byproduct of the reactions. Also, the raw material used to fuel the process, uranium, is itself a nonrenewable resource, and this technology is closely related with the production of nuclear weapons. Thus, while nuclear energy addresses the major concerns of traditional fossil fuels, it presents a new set of problems similar in nature to those presented by our current primary energy sources.

Hydrogen. Hydrogen fuel cells[1] have similarly developed as a product of a high technology push towards a clean and renewable fuel supply. While this fuel source has shown promise, particularly in the area of transportation, which currently represents a significant percentage of global and national energy consumption, it is as yet only produced in laboratories at the bench scale, and not commercially (DOE 2008). Remaining issues needing to be addressed include the lifecycle emissions of the process, particularly in the compression of the

1 A fuel cell is an electrochemical energy conversion device, which produces electricity and water from hydrogen and oxygen (Nice and Strickland 2008).

hydrogen to a useable form, as well as the infrastructural changes necessary to make the fuel widely available.

Solar Power. The conversion of solar radiation to electricity through photovoltaic cells has been an area of research for several decades. While the technology is proven and commercially available, it continues to be produced in a minimal amount, providing only 0.04% of the global primary energy supply in 2004 (IEA 2007). Strengths of this source include its renewability and carbon neutrality beyond the manufacturing and installation of the solar panels. Limitations include the relatively low efficiency of conversion, concerns over the embodied energy of the solar panels themselves, and the amount of area required to produce significant flows of electricity. Also, depending on the latitude and local climate, solar power may not be available in consistent supply.

Wind. Wind turbines have been making increasing contributions to the electricity grid in the U.S. and globally, experiencing a 48.1% annual growth rate worldwide from 1971 to 2004, although still providing only a minimal contribution of 0.06% to the world primary energy supply (IEA 2007). Like solar, wind power is renewable and carbon neutral once turbines are installed. However, wind power is geographically limited to a further extent than solar power and has been questioned as a possible threat to migratory birds.

Hydroelectric. Hydroelectric is perhaps the most proven and developed of the renewable energy sources, providing 3% of the national energy supply (EIA 2008). Limitations include the detrimental impacts on waterways and the associated ecosystem, geographical availability, and the increased evaporation of water from reservoirs of dammed rivers competes with the use of water for irrigation and municipal purposes.

Geothermal. Although geothermal energy is an environmentally benign, renewable energy source, it accounts for less than one half of one percent of the total global primary energy supply, and is not currently considered as capable of meeting any significant proportion of global or national energy demand (EIA 2008).

Biomass. Biomass energy, or bioenergy, refers to production of heat, electricity, and/or liquid fuels from any recently living matter. Currently, bioenergy represents about 3% of the energy consumption of the U.S. (EIA 2008). It is widely produced in developed countries in the form of ethanol from corn grains (*Zea mays*), sugar cane (*Saccharum sp.*), or cellulosic materials; as biodiesel from soybeans (*Glycine max*), jatropha (*Jatropha curcas*), or rapeseed (*Brassica napus*); and electricity through cogeneration with coal. Furthermore, the abundance of arable land along with industrial agricultural infrastructure in the U.S. provides a competitive advantage to the nation in terms of potential to produce a significant quantity of biofuel. One study by the USDA and USDOE reports a 1.3 billion ton annual supply of biomass available for energy production (Perlack *et al.* 2005). This amount is capable of displacing 30% of the petroleum currently used annually. Biomass has surpassed hydropower as the nation's largest domestic source of renewable energy, providing 3% of the energy in the U.S. and is unique from other renewable fuel sources such as solar and wind power because it can be converted to a liquid transport fuel (EIA 2008).

Many concerns, however, have been raised over the use of biofuels. These include the competition for land between food crops and energy sources, various technological and economic barriers to widespread production and use, and debate over the net energy balance (NEB) and extent of GHG emission reductions in the light of land use changes associated with expanded feedstock production. Pimentel and Patzek (2005) reported greater energy inputs than outputs for several biofuels, including ethanol from corn grain, switchgrass (*Panicum virgatum*) and wood biomass, as well as biodiesel from soybean and sunflower (*Helianthus annuus*). Hill *et al*. (2006) report high costs of production for ethanol and biodiesel. Ethanol from corn grain is reported at \$0.68 per energy equivalent gallon of gasoline as compared with \$0.65 per gallon of gasoline. Biodiesel from soybean is reported at \$0.81 per energy equivalent gallon of diesel, whereas petroleum based diesel is reported at \$0.68 per gallon. Recent studies by Searchinger *et al*. (2008) and Fargione *et al*. (2008) demonstrate the concerns over GHG emissions associated with land use conversion for increased biofuel production and to meet demand for commodities offset by increased biofuel production. Furthermore, these limitations have generated to some extent a public perception opposed to the increased production of biofuels, ethanol, in particular. Despite these limitations, bioenergy does present a significant potential as an energy source. Farrell *et al*. (2006) found that when co-products are incorporated in the allocation of energy, the energetic yield of ethanol production is much more competitive. Hill *et al*. (2006) report positive energy outputs for both corn grain ethanol and soybean biodiesel. They also report environmental benefits associated with biofuel production, including reduced GHG emissions and other air pollutants.

In terms of the U.S. there is an expanse of arable land capable of producing vast quantities of biomass (Perlack *et al*. 2005). This domestic supply would alleviate the economic and political concerns associated with oil consumption. Furthermore, the development of domestic industries through bio-refineries capable of producing a multitude of products, chemicals, and fuels from biomass may further decrease dependence on oil for uses other than energy. For example, Amidon *et al*. (2008) discuss the potential for production of reconstituted wood products, particleboard, fuel pellets, chemicals, pulp, electricity, and fuels from woody biomass. This would additionally enhance rural livelihoods and help to sustain lands in agriculture and forestry.

Biofuels are considered to be carbon neutral in the sense that the carbon emitted upon combustion is equivalent to the amount of carbon recently sequestered by the growing of the biomass feedstock itself. When compared with fossil fuels, which release ancient geologically sequestered carbon upon combustion, biofuels have been encouraged as an alternative to some of the fossil fuels currently in use. Although the environmental benefits, and GHG emission reductions in particular, have been called into question in light of land use changes associated with additional biofuel feedstock production, a number of studies indicate a significant potential for environmental benefits from biofuels if managed appropriately (Farrell *et al*. 2006, Hill *et al*. 2006, Schmer *et al*. 2008, Tilman *et al*. 2006).

Furthermore, the flexibility of bioenergy as an energy source is an attractive quality. Being convertible into electricity and liquid fuels for transport is a promising opportunity for biomass as an energy source due to the demand for liquid transport fuels, especially considering the lack of conversion flexibility of the alternative energy sources discussed above. Recognizing this unique characteristic, the U.S. government has passed legislation, such as the Energy Independence and Security Act of 2007 and the 2008 Farm Bill, aimed at further developing the biofuel industry, with a specific emphasis on cellulosic ethanol.

U.S. Energy Policy

There is a growing interest in the area of alternative energy sources such as bioenergy. Globally, the production of biofuels has been increasing steadily (Figure 1-5). This has been driven in part by the passage of the of Kyoto protocol, a global agreement aimed at “stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system” (UNFCCC 2008). National policies like the

"Twenty in Ten" initiative of reducing U.S. gasoline usage by 20% in the next ten years, aim to utilize biofuels as a way of achieving this goal, with a mandatory fuels standard requirement of 36 billion gallons of renewable and alternative fuels in 2017 (EISA 2007). Central to this goal is the development of cellulosic ethanol and making it cost competitive at a modeled cost for mature technology at $1.20 per gallon by 2017 (DOE 2007). An increased demand in ethanol is stimulated by the phase out of methyl *tert*-butyl ether (MTBE) as an octane enhancer of reformulated gasoline, as well, and facilitated by the Volumetric Ethanol Excise Tax Credit (VEETC) which provides blenders and retailers of ethanol a subsidy of $0.51 per pure gallon of ethanol blended (EERE 2008).

Biofuels and Cellulosic Ethanol

The large scale commercial production of ethanol in the U.S. has previously been limited primarily to that produced from the corn grain feedstock, rather than the cellulosic ethanol production process capable of fermenting the sugars locked in the cellulose and hemicelluloses of plant fibers found in grasses, corn stalks, and trees. The limiting factor to cellulosic ethanol production has heretofore been technological and economical. The production process is too costly per unit of ethanol produced at $1.89 to $2.27 per gallon to be competitive with corn grain ethanol or gasoline (Perrin *et al*. 2008). However, the opportunity for ethanol production from cellulosic materials is far greater than that of corn grain ethanol based on the available lands and biomass available. Furthermore, the production of ethanol from cellulosic materials avoids "food vs. fuel" conflicts, making available crops grown on marginal lands and harvest residues rather than using food crops such as corn and soybeans for fuel production. The use of small diameter wood from overstocked non-industrial private forest (NIPF) pine plantations in the U.S. South represent a feedstock for cellulosic ethanol production that may be beneficial to the NIPF owners economically and the health and productivity of the forest land as well. Removal of small diameter trees in overstocked stands allows for the additional growth of larger trees with a higher merchantable volume by reducing the competition for soil nutrients, light, and water (Nebeker *et al*. 1985). Also, thinning planted pine stands can help reduce the risk of wildfire, pest, and disease outbreak, maintaining not only the investment of the owner, but also the ecosystem services provided to society, such as increased soil, air, and water quality (Carter and Jokela 2002). Therefore the thinned material and un-merchantable harvest residues of planted pine NIPFs may be an economical source of feedstock material for cellulosic ethanol conversion.

Based on this rationale, several government initiatives have been passed at the state, federal, and international level encouraging the production of biofuels from various agricultural and forestry feedstocks. The state of Florida currently has various incentive, rebate, and grant programs available for businesses, organizations, and residents interested in using renewable energy technologies (Florida DEP 2008). In particular, the Florida Farm to Fuel initiative is aimed at educating the public and enhancing the market for renewable energy from crops, agricultural waste and residues, and other biomass (Florida Legislature 2007). At the national level, President Bush has signed the Energy Independence and Security Act of 2007, which includes a Renewable Fuels Mandate, calling for an increase in the supply of renewable fuel to 36 billion gallons by 2022 (EISA 2007). The 2008 Farm Bill also includes a $1.01 per gallon production tax credit for plants that produce cellulosic ethanol (USDA 2008). Internationally, biomass based energy projects have been registered by the Clean Development Mechanism (CDM) of the Kyoto Protocol, aimed at reducing global GHG emissions (UNFCCC 2008).

Although the policies discussed are aimed towards increasing energy security and environmental benefits over fossil fuels, there is debate within the scientific community as to what extent biomass based fuel sources are beneficial towards these goals. The majority of biofuel in the U.S. is currently produced from cornstarch with ethanol production accounting for 13% of domestic corn production in 2005 and 20% in the 2006/2007 marketing year (Park and Fortenbery 2007). This scenario has led to concern over increasing corn prices and the so-called "food vs. fuel" debate. Additionally, the energy ratio of cornstarch based ethanol has been questioned, being reported as less than one by Pimentel and Patzek (2005) at 0.71 and marginally greater by Hill *et al*. (2006) at 1.25. More recently, the impacts of land use change have been considered in calculating the net GHG emissions from biofuel production, indicating that the conversion of grasslands, peat lands, tropical forests, and other intact ecosystems to grow energy feedstocks far outweighs the GHG offsets of burning biofuels rather than fossil fuels (Fargione, *et al*. 2008, Searchinger *et al.* 2008). For these reasons, alternative ethanol feedstocks and conversion processes are under consideration to meet the goals set out by the President and U.S. government within the Renewable Fuels Mandate. In particular, the bill calls for 16 billion gallons of cellulosic biofuel production by 2022 (EISA 2007). Cellulosic ethanol can be produced from a wide variety of plant biomass including species capable of growing on lower quality, or marginal lands, crop residues, and woody biomass. This feedstock flexibility represents an opportunity to utilize undervalued materials for biofuel production without accelerating the conversion of intact ecosystems or increasing GHG emissions. This opportunity may also provide landowners with an expanded market for their agriculture and forest products.

Sources of Biomass

All of the biomass available in the U.S. for biofuel production comes from the two general categories of agriculture and forestry. This includes: crops, residues, fuel reduction treatments, manure, processing residues, post consumer residues, and landfill gases.

Agriculture. Currently a vast majority of bioenergy feedstock is produced from agriculture. This includes corn grains, sugar cane, soybeans, and other crops grown directly for conversion into biofuels. As the technology for cellulosic ethanol production continues to develop, an increasing amount of residues such as corn stover and sugar cane bagasse are being considered for biofuel production. Also, in many livestock and dairy operations, manure and other animal wastes are utilized for biogas production to help fuel operations. Also available are the many residues and waste products associated with feed and food processing, and finally, municipal solid waste, post consumer residues, and landfill gases are available for conversion to energy end products (Perlack *et al*. 2005). Perlack *et al*. (2005) estimate the total current availability of biomass from croplands at 194 million dry tons per year.

Forestry. As cellulosic ethanol technology continues to develop, forestry appears poised to play a major role in bioenergy production. Already, forest industries produce a majority of energy for pulp and sawmill operations through electricity production from combusting bark and other residues (Nilsson *et al*. 1995). The major opportunities for bioenergy in the forestry sector include the use of logging residues and biomass removed during land clearing operations. Also, fuel reduction treatments aimed at reducing the risk of wildfire, pest outbreak, and increasing yields from remaining trees represent a significant amount of biomass available for bioenergy production at 60 million dry tons (Perlack *et al*. 2005).

Forests in the U.S. South

Forestland Extent

The geographic location of the U.S. South provides favorable conditions for forest growth. An abundance of land, rainfall and moderate temperatures have allowed the Southern states to expand their forestry enterprises over the past century. The South is estimated to have more than 214 million acres of forest land, 91% of which is designated as timberland, land with enough productivity to make timber production possible (Wear and Greis 2002). In particular, there has been a marked increase in the intensively managed pine plantations, from less than 2 million acres in the 1950s to 32 million acres at the end of the 1990s (Fox *et al.* 2004). These high intensity plantations have allowed for the production of increased yields of timber and pulpwood to meet the rising demands of a growing population on a limited area of land. As a result, the Southeastern states of the U.S. provide a significant proportion of the nation's timber and other forest products.

Ownership

NIPF owners control about 69% of the 201 million acres of timberland in the Southeastern states (Wear and Greis 2002). The Southern states produce nearly 60 percent of the nation's wood output and, in 1997, contributed to about 2.2 million jobs and $251 billion of total industry output (including indirect and induced jobs and income). This represents 5.5% of jobs and 7.5% of total industry output in the South (Wear and Greis 2002).

Species

There are several classifications of species grown on Southern forestlands. Foremost among these are the pine plantations. The dominant species of the pine plantations are slash pine (*Pinus elliottii*) and loblolly pine (*Pinus taeda*). In Florida, slash pine (*Pinus elliottii*) is a dominant forest species, covering approximately 5.1 million acres, or 34% of the total forestland in the state (Carter and Jokela 2002).

Ecosystem Services

In addition to the financial benefits associated with forestlands, there are many non market values associated with these lands, ecosystem services, in particular. These include water filtration, soil stabilization, climate moderation, carbon sequestration, biodiversity, and wildlife habitat are associated with forested lands (Carter and Jokela 2002). Although forest owners do not generally receive payment for these ecosystem services, they certainly represent a valuable benefit to the society.

Current Trends and Outlook of Forestlands

Threats and opportunities. Falling stumpage values of timber, chip and saw, and pulpwood in recent years (Timber Mart South 2008) has threatened the economic viability of maintaining NIPFs as forest lands as these products represent the major source of income to the forest owner (Figure 1-6). Due to the diminished returns from thinnings and other small diameter wood, there is less incentive for landowners to conduct this management practice. This leads to a situation in which forests become overstocked, increasing the risk of wildfire, pest outbreak, and disease, while simultaneously decreasing the value of the dominant trees through competition for the nutrient resources of the soil (Nebeker *et al*. 1985).

Role of bioenergy. One alternative use of small diameter wood is as a cellulosic ethanol feedstock. The use of small diameter forest biomass in the U.S. Southeast region represents an additional opportunity to increase the health and profitability of forestlands, particularly for NIPF owners, as well as potentially provide a significant amount of feedstock for ethanol production.

Problem Statement

A multitude of concerns associated with the continued use of fossil fuels as a primary energy source in addition to the unique challenges and opportunities of NIPF owners of the U.S. South have produced a considerable interest in the use of forest biomass as a feedstock for bioenergy, and specifically, for ethanol production. However, there are large gaps in our knowledge and understanding regarding fundamental aspects of producing ethanol from Southern NIPF biomass. These include the economic implications to the forest owner and the larger forestry and energy industries, the energy balance of the process, and the environmental impacts of the entire life cycle of the process.

Research Significance and Objectives

The area of forest bioenergy is gaining increasing amounts of attention from a variety of stakeholders both within the U.S. and abroad. Given the recent legislation passed by the U.S. federal government calling for 16 billion gallons of annual cellulosic biofuel production by the year 2022, this interest is likely to increase in coming years (EISA 2007). This study aims to address some of the fundamental questions related to the production of cellulosic ethanol from Southern NIPF lands, analyzing slash pine as a representative species of the pervasive pine plantations. These questions include:

- What is the profitability of NIPF lands under various biomass production scenarios in conjunction with production of traditional forest products of pulpwood and sawtimber?
- What is the cost of producing ethanol in this method?
- What is the energetic yield of ethanol produced from forest biomass considering the inputs throughout the entire life cycle from seed collection to seedling and plantation growth, harvesting, and conversion to ethanol?
- What are the environmental impacts associated with the life cycle of the process?
- What is the total annual ethanol supply potential from Southern pine plantations on NIPF lands?

In order to address these research questions, the analysis undertaken consisted of two major components, a cost benefit analysis (CBA) and a life cycle assessment (LCA). The CBA portion addresses the economic questions of forestland values in the light of a market for biofuels and unit cost of cellulosic ethanol production from forest biomass, while the LCA considers the energetic and environmental implications of the process. Figure 1-7 presents a visual representation of the conceptual framework of the study.

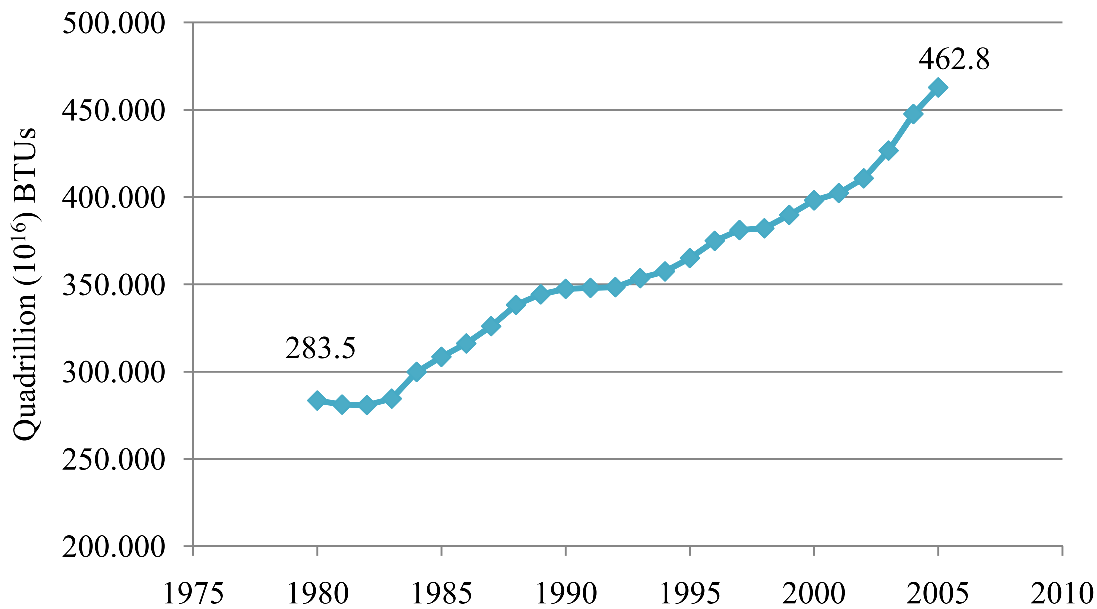

Figure 1-1. Total global primary energy consumption from 1980 to 2005 (EIA 2007).

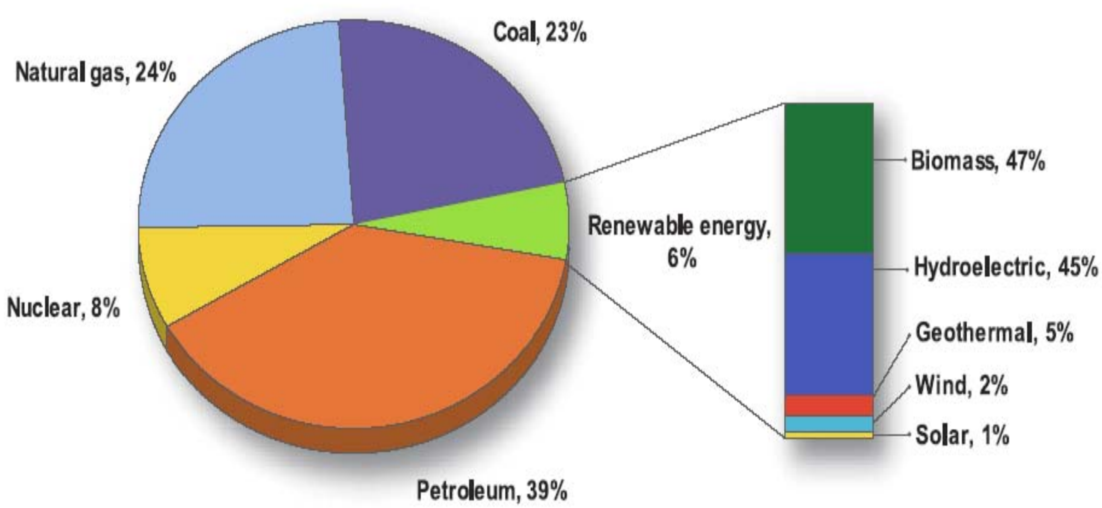

Figure 1-2. Total U.S. energy consumption by source, 2004 (EIA 2004).

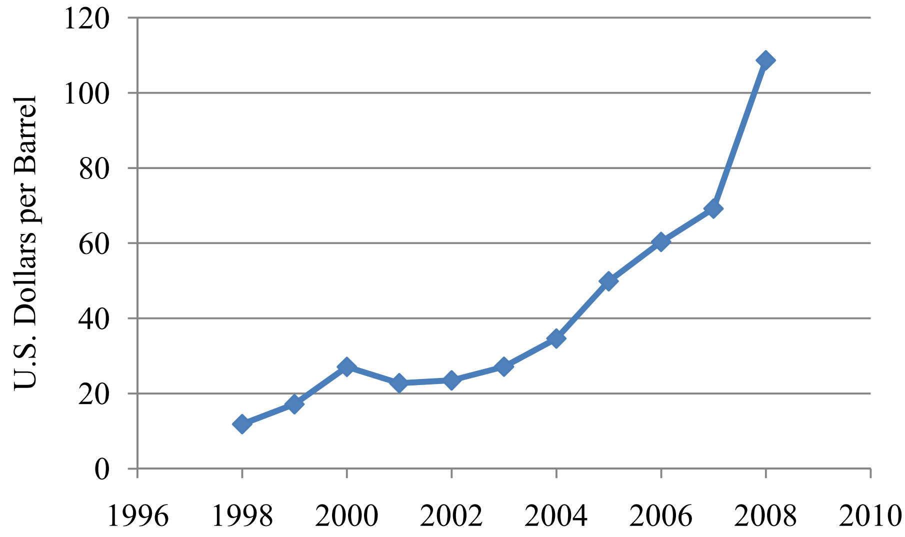

Figure 1-3. World spot price of crude oil for 1998 to 2008 (EIA 2008).

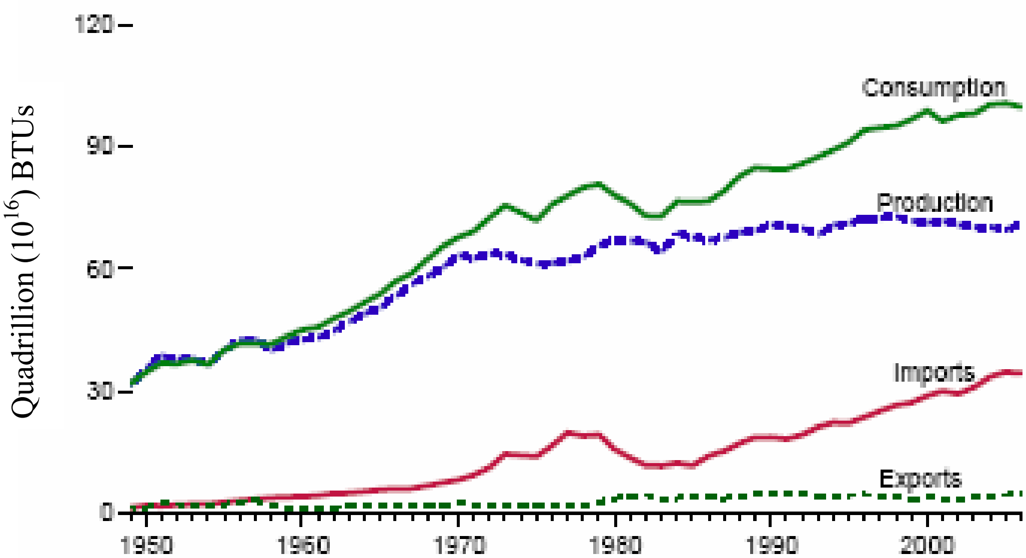

Figure 1-4. U.S. Energy Production, Consumption, and Trade. (USDOE/EIA Annual Energy Review 2006)

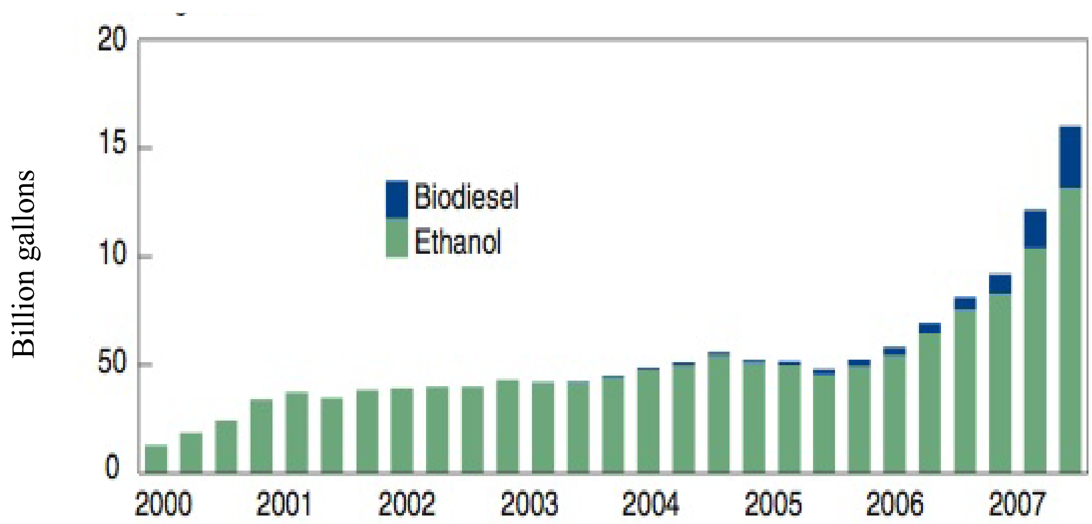

Figure 1-5. Global ethanol and biodiesel production from 2000 to 2007 (IEA 2008).

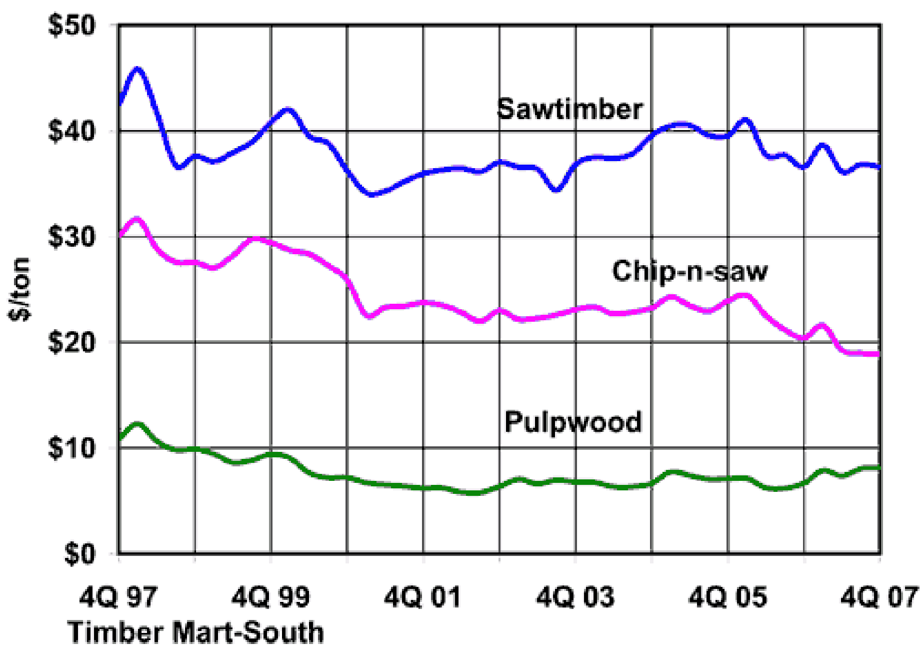

Figure 1-6. Ten year price trends for pine pulpwood, chip and saw, and sawtimber. (Timber Mart South 2008)

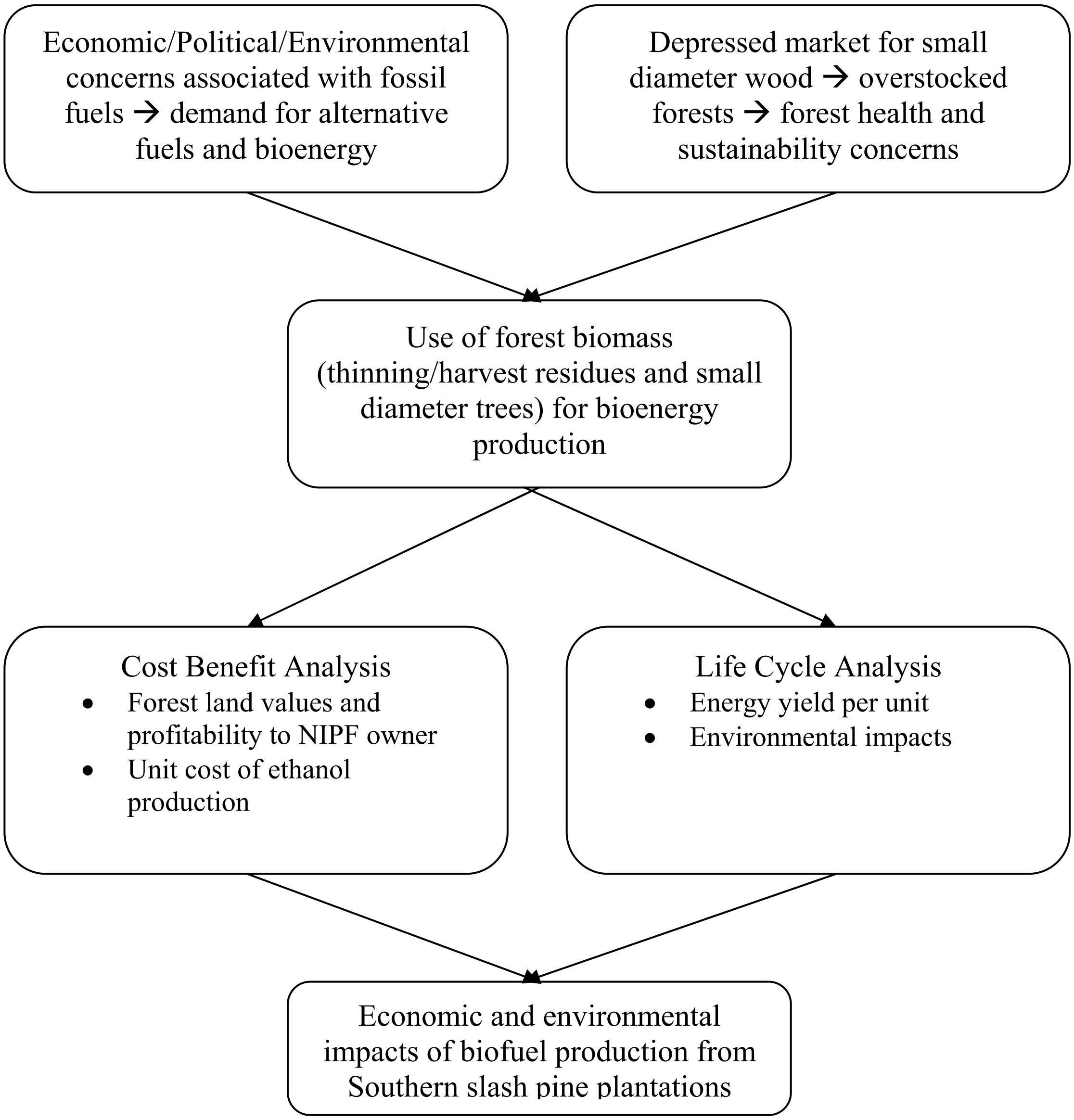

Figure 1-7. Conceptual framework of research design and objectives.

CHAPTER 2
ECONOMICS OF ETHANOL PRODUCTION FROM FOREST BIOMASS

Introduction

The economics of ethanol production from intensively managed slash pine stands in the Southeastern coastal plain is critical in determining the sustainability of this fuel source, both in terms of the unit cost of ethanol produced and the profitability to the forestland owner. This chapter is divided into two major sections corresponding with the analysis undertaken: 1) forestland values in the face of a biofuels market, and 2) unit cost of ethanol production considering the two-stage dilute sulfuric acid conversion process. Both sections incorporate uncertainty through sensitivity and risk analysis. The first section considers profitability to the forest owner under several biofuel feedstock production scenarios: with and without thinning, use of harvest residues, use of varying proportions of pulpwood size logs, and use of total harvest. The second section calculates the cost of production per liter of ethanol based on the necessary inputs to the system. The use of sensitivity analysis and risk modeling[2] to determine the variables most influential to the analysis as well as their effects on the final outcomes is applied to both sections through use of the Excel add-in @Risk software.

Forestland Value

The value associated with producing ethanol from NIPF slash pine plantations in addition to pulpwood, chip and saw, and sawtimber was determined by comparing the profitability of various production scenarios. Typically, NIPF owners in the U.S. South manage their lands to maximize profitability based on a variety of outputs. These include the recreational and

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2 Sensitivity analysis is used to determine the effect on the final outcome considering specifically defined values for a given variable, whereas a risk analysis iteratively calculates the output value based on a distribution for the input variable, as defined by the analyst. These analyses are performed for the purposes of determining the sensitivity of the model's outcome to any given variable, and to provide a probability associated with any given outcome, respectively.

ecological benefits associated with sustainable forestry in addition to production of pulpwood, timber, and nontimber forest products (NTFP) such as pine straw, mushrooms, and berries (Tilley and Munn, 2007). The management practice of the forest owner is influenced by the prevailing market conditions. In this analysis carbon sequestration is considered as a marketable product of the plantation. Thus, the optimal profitability to the forest owner is determined by comparing the monetary values associated with various combinations and distributions of the forest products considered, including: pulpwood, chip and saw, sawtimber, pine straw, hunting rights, carbon credits, and ethanol feedstock. These outputs are not all encompassing of forest products, but are chosen for this analysis because they represent what a typical NIPF owner can expect to produce from a given acre of pine plantation in the Southern U.S. region.

Ethanol Unit Cost of Production

The unit cost of ethanol production is calculated based on the capital investments and operating costs specific to the growth and conversion of the feedstock being considered. Determining the unit cost is useful in order to compare the market competitiveness of various ethanol production pathways with other biofuel and petroleum based systems. Along with environmental and social sustainability, the economic competitiveness of production is central to determining the relative viability of a particular energy source over the long term.

Central to the unit cost of production is the status of the technological design of the process pathway. The system considered in this analysis includes the high intensity silviculture associated with modern forest management[3] of the pine plantations of the Southern U.S. and the two-stage dilute sulfuric acid conversion process as described by Kadam (2002). A process description is presented in Appendix A. This process is considered due to its well studied

3 This refers to the use of highly mechanized equipment for site preparations, planting, thinning and harvesting, the use of fertilizers and herbicides, and prescribed burnings.

methodology and process design, but is not necessarily the most advanced or promising technique for cellulosic ethanol production. As processes such as enzymatic hydrolysis are further advanced and conversion efficiencies improved, unit cost is expected to be correspondingly reduced, increasing the cost competitiveness of ethanol amongst the liquid transport fuel options.

Method

This section is organized based on the two components analyzed. First the profitability analysis is discussed. Growth and yield model specifications are given followed by a description of the valuation techniques utilized. Second, the unit cost analysis is described beginning with a report of the inputs to and process of ethanol production and ending with the description of the unit cost calculation.

Forestland Value

In order to determine the profitability of NIPF lands under various biofuel production scenarios, the land expectation value (LEV) was calculated for all situations considered. The calculation for LEV was first derived by Faustmann (1849). This calculation determines the net present value of bare land in perpetual timber production, assuming identical rotations, and is often used to value even aged pine plantations (Bullard and Straka 1996). The formula for the LEV calculation is given below (Formula 2-3).

In order to simulate conditions on a typical acre of pine plantation, forest stand data were simulated using the Georgia Pine Plantation Simulator (GaPPS) 4.20 growth and yield simulation program developed by Bailey and Zhou (1998). Above and below ground forest biomass was calculated for each year from 5 to 40 of the simulated plantation. The model specifications defined within GaPPS include even-aged rotations of slash pine grown in the lower coastal plain fertilized at year five with nitrogen and phosphorus on a “C” group soil[4] based on the fertilization model developed by the Cooperative Research in Forest Fertilization (CRIFF) group at the University of Florida (Jokela and Long 1999). A spacing density of 720 trees per acre at age five was assumed, with a site index of 70 feet at a base age of 25 years, and a 15% canker infection rate. The total outside bark green weight was divided into 4 product classes based on small end diameter, minimum length, and length increment (Table 2-1). Three stands were simulated from year 5 to 40. One stand was simulated as an un-thinned stand, one stand was simulated with a thinning at year 15, and the final stand was simulated with a thinning at year 12 and another at year 20. Each thinning is assumed to remove 30% of the standing trees (Figure 2-1). Below ground biomass was calculated from the growth and yield data obtained through GaPPS based on the assumption that below ground biomass of the tree represents 30% of the total tree weight (Eric Jokela, pers. comm., University of Florida, May 23, 2008). Total carbon within the biomass was calculated assuming that carbon accounts for 50% of the total oven-dry biomass of the tree (FAO 2003). From these calculations the income to the forest owner was calculated based on the revenues from timber harvest, carbon payments, hunting lease, and pine straw harvest.

The costs considered in the model include site preparation, which consists of chopping, piling, burning piles, bedding, and herbicide application, seedlings, planting, fertilizer treatment in year five, herbicide application in year six, prescribed burn in year 11, and a yearly tax rate (Table 2-2). Cost values were based on Smidt *et al.* (2005), Andrew’s Nursery (2007), and Natural Resource Planning Services, Inc. (Matt Simpson, pers. comm., NRPS Inc., March 24,

4 This soil type was developed on coarse textured sediments low in weatherable minerals typical of Florida.

2008). Costs were discounted to present values (PV) using the continuously discounted formula of:

$$PV = FV * e^{-r*t} \tag{2-1}$$

where FV is the future value, e is the base of the natural logarithm, r is the discount rate, and t is the year in which the costs are incurred. In this case a real discount rate of 5% was used. The discount rate chosen to assess the value of the forestlands is half that of the rate used to assess the unit cost of ethanol production (10%) due to the differing nature of the investments. Forestry is generally a long-term investment with few inputs between the initial stocking and final harvesting, decreasing the dependence of the return on investment upon outside market forces and therefore decreasing the risk to the forest owner. Other studies have generally suggested a similar discount rate for forestry investments ranging from 4 – 7.4% (Row *et al*. 1981, Bullard *et al*. 2002, Matta and Alavalapati 2005). Values were then accumulated to arrive at a cumulative present value of costs every year from year 0 to 40.

The nontimber benefits included in the model are hunting lease payments, pine straw harvest, and carbon credits. Hunting lease payments were assumed to be $10.00 per acre per year beginning in year five and continuing every year until stand harvest (Carter and Jokela 2002). Pine straw is considered to be harvested every three years beginning in year six until the first thinning is conducted, or a maximum of six times during the rotation if there is no thinning. Although revenues from pine straw harvest are significant at $100.00 per acre, pine straw is assumed to be collected only once every three years to avoid deleterious effects of decreased soil nutrients, such as reduced timber yields (Duryea 2003, Minogue *et al*. 2007). Carbon payments were calculated based on the current value per tonne of carbon dioxide as listed on the Chicago Climate Exchange at $6.00 per tonne (CCX 2008). Thus, the incremental change of total carbon stored in the above and below ground biomass on the site is multiplied by the market rate per ton of carbon for each year of the rotation, simulating payment to the landowner in each year of the plantation. Based on the model of the CCX, the landowner is considered a carbon offset, or credit, provider. The credits must be verified and aggregated through a third party who receives payment for their services. For this analysis, due to the uncertainties involved surrounding the issues of carbon sequestration permanence the rental payment approach was employed as described by Sedjo and Marland (2003), where the landowner receives a rental payment for the carbon sequestered per year with no expectation of permanent sequestration. All values were discounted using Equation 2-1. The discounted values were then accumulated for each year to arrive at a cumulative present value of nontimber benefits for each year from 5 to 40.

The value of the timber benefits to the land owner was determined using current South-wide averages for stumpage values of pulp wood, chip and saw, and sawtimber obtained from Timber Mart South (Table 2-3) in conjunction with the biomass and carbon data previously calculated. The growth and yield data provided by GaPPS was divided into the four size classes shown in Table 2-1 for each year of the plantation from year 5 to year 40. The value of harvesting the stand for purely timber benefits was calculated in each year from year 5 to year 40 as well by multiplying the current price for the particular product class by the outside bark green weight contained within that size class as obtained through GaPPS. These values were summed with the nontimber values and costs associated with site preparation and silvicultural treatments to obtain the cumulative NPV of the stand in every year from zero to 40, given below as formula 2-2:

$$NPV = PVt + PVnt + PVc \tag{2-2}$$

where PVt is the present value of timber benefits, PVnt is the present value of nontimber benefits, and PVc is the present value of costs.

Land valuation was conducted for varying scenarios of biofuel feedstock production as a proportion of the total timber harvest, harvest residues and thinned material available in any given year. A stumpage value of $5.00 per ton was assumed for all biomass delivered to the ethanol mill. Six biofuel feedstock production scenarios were considered separately under each of the three stands (Table 2-4):

- **Scenario 1:** No biofuel feedstock
- **Scenario 2:** Harvest residues only
- **Scenario 3:** One quarter of pulpwood plus residues
- **Scenario 4:** One half of pulpwood plus residues
- **Scenario 5:** All pulpwood plus residues
- **Scenario 6:** Full harvest plus residues

All pulpwood, chip and saw, and sawtimber not considered as biofuel feedstock are assumed to be sold in the market at the stumpage rates given in Table 2-3.

In the two stands simulated for thinning, the thinned material was considered as pulpwood. Although this biomass was accumulated only in the year of the thinning, the PV was calculated according to the six scenarios listed above was added to the PV calculated for each year following the thinning as well in order to account for the benefit to the landowner. Thus, much like the costs and nontimber benefits, the values of the scenarios under the thinned stands were accumulated to determine a cumulative PV for each year. The NPV in each year was then used to calculate the LEV, which returns the value of the stand under consideration assuming perpetual rotations. LEV was found by solving the Faustmann formula (1849):

$$\text{LEV} = \frac{\text{NPV}}{1 - e^{-r*t}} \tag{2-3}$$

where e is the base of the natural logarithm, r is the discount rate, and t is the rotation length. The LEVs were used to compare the different scenarios. These values were also used to calculate the equivalent annual values (EAV), which is simply the lump sum value converted into an annuity, calculated with the following formula.

$$\text{EAV} = \frac{\text{LEV}*r}{1 - e^{-r*t}} \tag{2-4}$$

In order to account for the uncertainty inherent to the forestland valuation, the Excel add-in @Risk software was utilized to conduct sensitivity analysis and quantify the probabilities of the determined results. The variables subjected to risk analysis in the forest stand value simulations included the stumpage values for pulpwood, chip and saw, sawtimber, and biofuel feedstock, and the discount rate. These variables were included as the inputs to the @Risk model, whereas the maximum LEV calculated for each of the six scenarios in all three stands (18 total) were incorporated as the output. Ten thousand iterations were performed for each of the Monte Carlo simulations. Monte Carlo simulation is a stochastic method of determining the probability of an output based on the combination of probability distributions of the uncertain inputs (Iordanova 2007). Probability distribution functions indicating the likelihood of a given LEV based on the results of the iterations performed within the Monte Carlo simulation were determined and sensitivity analyses were calculated based on the results.

Ethanol Unit Cost of Production

In order to assess the economic viability of ethanol produced from forest biomass, the cost of production per unit of ethanol was calculated. For the purposes of this analysis the costs of production considered are ethanol mill construction costs (annualized over the lifetime of the plant), wages for all labor employed, delivered biomass feedstock, fuel, water, chemicals, and disposal of ash. Mill construction costs and wage data were obtained from the National Renewable Energy Laboratory (Aden *et al*. 2002). The plant output capacity is assumed to be 50 million gallons per year (MGPY) with a production life of 15 years. The costs for feedstock, fuel, water, chemicals, and disposal are calculated based on the amounts of each input necessary per year to meet the plant capacity of 50 MGPY. The amounts of each input per 264.2 gallons (1000 L) of ethanol produced are given in Table 2-5.

The ethanol production process considered is a two-stage dilute sulfuric acid hydrolysis (Appendix A). This particular conversion process is considered based on the large amount of established information regarding the use of dilute acid as a hydrolysis medium, with the first attempt at commercialization occurring in Germany in 1898 (DOE 2007). Thus, this process is also considered to be one of the more readily commercially available technologies, and the two-stage process results in high yields and purity levels (Harris *et al*. 1985).

Delivered feedstock costs include stumpage value to NIPF owner, harvesting and chipping, transportation, and profit to logger. Stumpage value of harvest residues was estimated based on published rates (Perez-Verdin *et al.* 2008, Petrolia 2006) and through personal communication with Timber Mart South (Sarah Baldwin, pers. comm., TMS, May 23, 2008) at \$5.00 per green ton. For harvesting and chipping a base value of \$9.18 per green ton was used based on Mitchell and Gallagher (2007) and which was verified through personal communication with a local forest harvester (Richard Schwab, pers. comm., M.A. Rigoni, March 11, 2008). For transportation, a \$0.15 per ton per mile was used according to a 100 mile (161km) haul distance to arrive at a total transport value of \$15.00 per ton (Timber Mart South 2008). Logger profit was based on a rate of \$4.00 per green ton (Richard Schwab, pers. comm., M.A. Rigoni, March 11, 2008). The total delivered cost based on these base case values was therefore determined to be \$33.18 per green ton. This value is consistent with other estimates of delivered costs for small diameter pulpwood and fuel chips (Perez-Verdin *et al*. 2008, Petrolia 2006). The value of gypsum produced was considered as a co-product to be sold at the market rate of \$30.00 per ton.

All costs and benefits were scaled up to the 50 MGPY capacity of the plant over the 15 year life of the plant to calculate the net present value (NPV) of the project. The NPV was calculated with the following formula:

$$\mathrm{NPV} = \sum_{t=1}^{15}[(B_t * e^{-r*t}) - (C_t * e^{-r*t})] \tag{2-6}$$

where t is the year in which benefits (B) and costs (C) are incurred, and r is the discount rate. In this case a real discount rate of 10% was chosen based on Short *et al.* (1995). 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 in the absence of statistical data on discount rates, 10% should be taken for projects with risks similar to renewable energy investments. The unit cost of ethanol was computed by means of the Excel Solver software; the cell with the NPV output is constrained to equal \$0.00 by allowing the input cell of the price of ethanol per liter to vary, which is linked in the Excel spreadsheet. Thus the "break even" cost of production per unit of ethanol was determined.

In order to account for the uncertainty inherent to the ethanol unit cost analysis, the Excel add-in @Risk software was utilized to conduct sensitivity analysis and quantify the probabilities of the determined results, as deemed necessary by Richardson *et al.* (2006) for ethanol production. The @Risk software was used to perform a Monte Carlo simulation on the delivered feedstock cost since this represents the largest single cost in the ethanol production process. In this case, the inputs are the four components of the delivered cost: stumpage value, harvesting and chipping, logger profit, and transportation. A triangular distribution was assumed for each of these components. A triangular distribution assumes a minimum, maximum, and most likely value as determined by the modeler. In this case, the most likely value was the base case value with 60% likelihood and the minimum and maximum values were set at 25% below and above the base case value, respectively (Table 2-6).

With these inputs and their given distributions, a Monte Carlo simulation was run to give the probability distribution for the total delivered feedstock cost. The simulation included 10,000 iterations and determined the mean delivery price to be $33.87. The bounds of the central 90% were correspondingly determined to be $30.62 and $37.11. The unit cost of ethanol production was modeled under each of the three values given above for the mean, and the upper and lower bounds of the 90% probability distribution centered on the mean to yield a range of values for the unit cost reflecting the uncertainty of the final delivered feedstock cost. Sensitivity analysis was also conducted to determine the input variables respective impact on the final cost per unit ethanol produced.

Results

Forestland Value

Land expectation values were found to be positive for all scenarios except the biofuel feedstock production only (scenario 6) at some point during the simulated rotation, indicating a profitable venture for the forestland owner. The un-thinned stand was the least profitable stand, with the highest LEV obtained from the biofuel feedstock production scenario of harvest residues (scenario 2), peaking in year 21 of the rotation at $739.98 per acre (Figure 2-2). The lowest yielding scenario in all stands was the maximum biomass production scenario, reflecting the higher values of chip and saw and sawtimber size class trees for their respective wood products than for biofuel production. The ranking of the six scenarios within each stand was the same across the three simulated stands. That is, the highest yielding scenario in terms of profitability in all stands was the biofuel feedstock production scenario of residues only going to bioenergy production (Scenario 2), followed by the scenario with 25% pulpwood plus residues (Scenario 3), then the 50% of pulpwood plus residues (Scenario 4), followed by timber only production (Scenario 1), 100% of pulpwood plus residues (Scenario 5) and finally, the use of all harvested trees as an ethanol feedstock (Scenario 6).

The maximum LEVs followed the same rankings of scenarios in the stand thinned at year 15 as well (Figure 2-3). All LEVs peaked at year 25 with the exception of the biofuel feedstock only scenario, which peaked at year 24.The maximum LEVs followed the same rankings of scenarios in the stand thinned at years 12 and 20 as well. All LEVs peaked at year 26 (Figure 2-4).

The results of the sensitivity analysis indicate that the discount rate is the most critical variable for determining the extent to which the NIPF land is profitable under the various biofuel feedstock production management scenarios. For all scenarios except the full harvest for biofuel feedstock, when the stumpage price of biomass was the critical factor, the discount rate was the variable with the strongest regression coefficient, consistently displaying values at or greater than -0.90, indicating that as the discount rate increases, the forestland value decreases. Similarly, as the discount rate increases, the rotation age decreases as well, based on the increased opportunity cost associated with carrying the capital costs. In the timber production only scenarios, the biomass price has no impact on the profitability of the venture, just as in the biofuel feedstock production only scenarios the pulpwood, chip and saw, and sawtimber stumpage values have no impact, as is to be expected. In the scenarios where all pulpwood is converted to biofuel feedstock, the stumpage price for pulpwood similarly has no impact on the profitability. In general, as more trees are devoted towards ethanol production, the stumpage rate for biofuel feedstock plays a more important role in the profitability of the forestland. The probability distribution functions for the three stands simulated are given in Figures 2-5, 2-6, and 2-7.

Ethanol Unit Cost of Production

The unit cost of ethanol was calculated to be \$2.12 per gallon (\$0.56 per liter) using the mean delivered feedstock cost of \$33.18 per green ton. Based on the lower energy content of ethanol relative to gasoline, the cost of an energy equivalent liter (EEL) and gallon (EEG) of ethanol were calculated to be \$3.13 per gallon (\$0.83 per liter). The largest single contribution to this cost is the cost of the biomass feedstock, which represents 48% of the unit cost of ethanol production. Annualized project investment, ammonia, and fixed operating costs represent the next three largest contributors at 20%, 7%, and 6%, respectively (Figure 2-8).

Electricity costs are offset in large part due to the combustion of lignin, a byproduct of the acid hydrolysis, which provides 85% of the total energy consumption of the plant. Based on the lower bound delivered costs of \$25.37 per ton, the cost of ethanol decreases to \$0.50 per liter, and feedstock represents 43% of the total cost of production, as compared to the higher bound cost of \$42.28 per ton, where ethanol costs \$0.63 per liter and the feedstock represents 55% of the total cost (Table 2-8).

The sensitivity analysis of the variables included in the ethanol production process demonstrates that the final unit cost of ethanol produced in the manner described from forest biomass is significantly impacted by the cost of delivered biomass. Results also show that biomass feedstock delivered cost is the most influential variable on the final cost of the ethanol produced. Feedstock is followed by the other major cost components of plant construction, electricity, and ammonia. These variables demonstrate r-square values of 0.876, 0.335, 0.265, and 0.213. The positive values indicate the direct correlation between the costs inputs and the final unit cost of ethanol produced; as the costs of production increase, so too does the unit cost of ethanol. The only variable exhibiting a negative r value is gypsum, the co-product of ethanol, which intuitively makes sense because as the value of the co-product increases the unit cost decreases. However, the impact of gypsum is minimal (r^2=0.024), reflecting its relatively low market value as compared to the inputs to the process. The regression values and rankings of the variables influencing the unit cost are given in Table 2-9 and the cumulative probability distribution function is presented in Figure 2-9.

Conclusions

The results of the analysis indicate that a cellulosic ethanol industry from forest biomass would increase the profitability of NIPF owners in the U.S. South. Of all biomass production scenarios considered, the most profitable was found to be the production of traditional forest products of pulpwood, chip and saw, and sawtimber in addition to the harvesting of residues for biofuel production. This scenario limits the impact of biofuel production on other forest product sectors, but also puts the most pressure on the forest resource base by removing all biomass grown on the site. This may lead to diminishing yields over time as soil nutrients are removed faster than they can be replenished. Current practices generally include a piling and burning of the collected residues from the previous harvest, which releases nutrients from the woody biomass back to the soil as ash. As is generally true for forestry, due to the inherently long time to project maturity, the choice of discount rate is important in accurately assessing the profitability of the venture.

Based on the results of this study in comparison with others (Hill *et al*. 2006, Perrin *et al*. 2008), ethanol production from slash pine using the two-stage dilute sulfuric acid process is currently not cost-competitive with corn based ethanol or gasoline in the absence of subsidization (Figure 2-10). The price gap may be narrowed as the 2^nd^ generation ethanol technologies continue to develop and become more efficient in converting woody biomass to ethanol, or integrating into bio-refinery arrangements. Shorter haul distances from the plantation to the mill correspondingly lower unit cost, as biomass transport costs generally range from one third to half of the total cost of production. It is possible that cellulosic ethanol will receive greater attention from investors and government agencies as the process develops. The passage of the 2008 Farm Bill by congress legislated a $1.01 per gallon tax credit for cellulosic ethanol plants for the five year period.

This analysis would benefit from the incorporation of the risks associated with an un-thinned stand, and reflecting this risk in the land value calculations in future studies. The basis of the land value calculations on the GaPPS growth and yield model is very significant in determining the results of the study. Development of a current growth and yield model would better reflect current conditions for Southern NIPF owners of pine plantations. Uncertainties regarding below ground biomass and accounting procedures for carbon offsets, as well as expected price increases for the trading value of carbon could also play a potentially significant role in impacting the results of the study. As more information is gained in these areas, those results can be incorporated and reflected in this study as well. A more thorough consideration of carbon credits would require a more standard allocation procedure for southern pine plantation carbon credits. Carbon credits could also be received by the operators of the ethanol production stage for using a biomass feedstock in comparison to fossil fuels. Investigating alternative species would increase the applicability of the current study. Similarly, various conversion technologies would also provide useful information. In particular, analyzing the cost of production of ethanol through the enzymatic hydrolysis process would provide further useful information, as this process promises to be more efficient than the two-stage dilute sulfuric acid process. Finally, the nontimber benefits included in this analysis do not represent the limits of forestland values, but are intended to be representative of the current conditions, and as conditions change, the incorporation of further nontimber and non-market values may enhance the analysis as well.

Table 2-1. Size distributions of four product classes in GaPPS of slash pine biomass grown in the lower coastal plain.

	Small End Diameter (inches)	Minimum Length (feet)	Length Increment (feet)
Residues	0.1	0.1	0.1
Pulpwood	2.0	5.0	1.0
Chip and Saw	6.0	8.0	4.0
Sawtimber	8.0	8.0	8.0

Table 2-2. Costs per acre associated with intensive slash pine plantation management in the U.S. South.

	No.	Price	Cost	Year
Site prep	1	$323.00	$323.00	0
Chopping/Shearing	1	$50.00	$50.00	0
Piling	1	$48.00	$48.00	0
Burning piles	1	$60.00	$60.00	0
Bedding	1	$105.00	$105.00	0
Herbicides	1	$60.00	$60.00	0
Seedlings	720	$0.06	$41.76	0
Planting	1	$45.00	$45.00	0
Fertilizer	1	$49.23	$49.23	5
Herbicide	1	$62.04	$62.04	6
Burning	1	$30.00	$30.00	11
Tax rate (per year)	1	$7.00	$7.00	All

Table 2-3. Pine stumpage prices for timber and biomass in the U.S. South (Timber Mart South 2008).

Size Class	$/ton
Pulpwood	8.11
Chip and Saw	18.88
Sawtimber	36.59
Residues	5.00

Table 2-4. Biomass feedstock production scenarios of a slash pine plantation.

	Size Class			
Scenario	Residues	Pulpwood	Chip and Saw	Sawtimber
1) None	-	-	-	-
2) Residues	X	-	-	-
3) One quarter pulpwood	X	0.25 X	-	-
4) One half pulpwood	X	0.50 X	-	-
5) All pulpwood	X	X	-	-
6) Full harvest	X	X	X	X

Note: An 'X' designates that the biomass in this size class is utilized for ethanol production in any given scenario. A number before the 'X', e.g. 0.25, indicates the proportion of biomass of the given size class used for ethanol production in the given scenario.

Table 2-5. Material and energy inputs and outputs per 1000 L of ethanol produced.

Inputs	Quantity	Units	Cost ($/unit)	Outputs	Quantity	Units	Cost ($/unit)
Biomass	4.66	Ton	33.87	Ethanol	1000.00	L	Varies
Hydrated lime	54.92	Kg	0.08	Gypsum	131.50	Kg	0.03
Water	15171.36	L	0.00				
NH_3	105.62	kg	0.37				
Diesel	5.25	gal	2.88				
H_2SO_4	202.79	kg	0.03				
Electricity	1468.60	MJ	0.03				
Ash disposal	326.63	kg	0.02				

Table 2-6. Delivered slash pine biomass feedstock cost components triangular distribution bounds.

	Minimum	Best Guess	Maximum
		($ per green ton)	
Stumpage Value	3.75	5.00	6.25
Harvesting and Chipping	6.89	9.18	11.48
Logger Profit	3.00	4.00	5.00
Transportation	11.73	15.64	19.55

Table 2-7. Land Expectation Values (LEV) and Equivalent Annual Values (EAV) for six scenarios of biofuel feedstock production under three Lower Coastal Plain slash pine stand simulations with differing thinning strategies.

Stand	Scenario	LEV ($/acre)	EAV ($/acre)
Un-thinned	1	298.20	21.82
	2	359.45	27.65
	3	337.77	25.98
	4	317.28	23.21
	5	283.02	17.31
	6	-256.59	19.00
Thinned, Year 15	1	684.14	35.47
	2	734.64	38.17
	3	713.43	37.00
	4	692.22	35.83
	5	649.80	33.49
	6	-63.35	-3.44
Thinned, Years 12 and 20	1	773.35	40.60
	2	821.33	43.12
	3	798.72	41.93
	4	776.10	40.75
	5	730.86	38.37
	6	-82.15	-4.31

Table 2-8. Range of ethanol costs based on changing delivered feedstock price and the feedstock percentage of the total cost of ethanol production.

	Cost of Ethanol ($/L)	Feedstock Delivered Cost ($/green ton)	Feedstock percentage of total ethanol production cost (%)
Low Value	0.50	25.37	43
Mean Value	0.56	33.18	48
High Value	0.63	42.28	55

Table 2-9. Regression coefficients and rank of influence of variables impacting the unit cost of production.

Rank	Name	Regr
1	Feedstock	0.904
2	Plant Construction	0.293
3	Electricity	0.234
4	NH_3	0.188
5	Diesel	0.073
6	Ash disposal	0.033
7	Water	0.029
8	H_2SO_4	0.027
9	Labor	0.022
10	Gypsum	-0.021
11	Lime	0.020

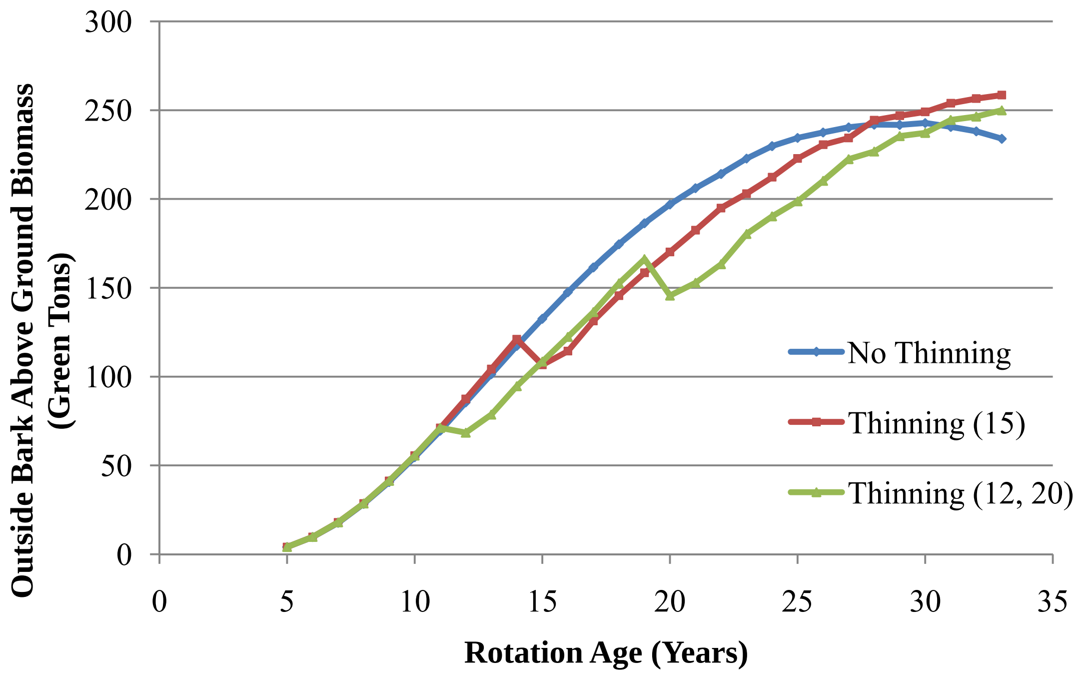

Figure 2-1. Growth and yield simulations of three slash pine stands.

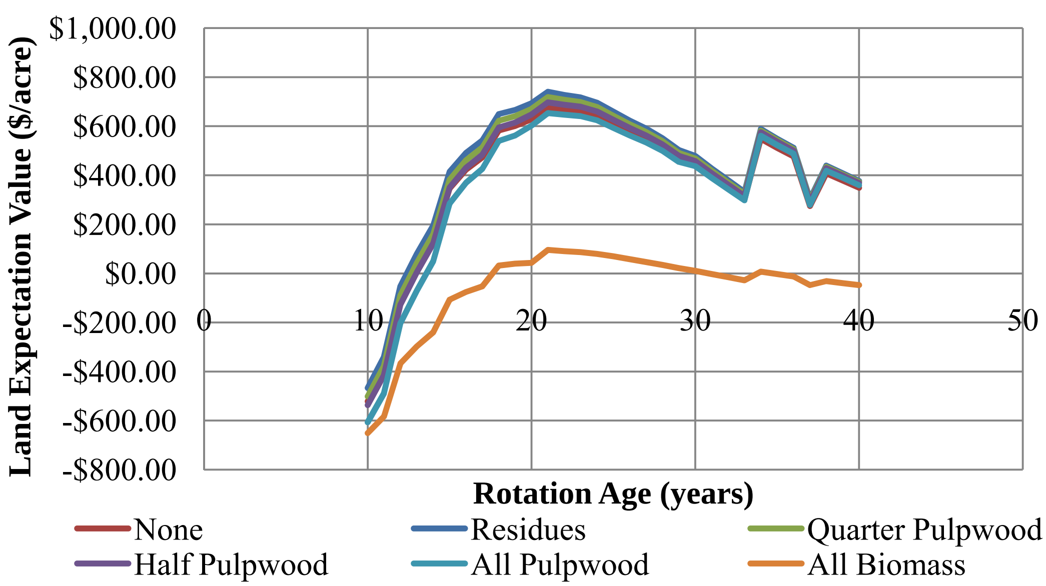

Figure 2-2. Land expectation values for six biofuel feedstock production scenarios in an un-thinned slash pine plantation in the lower coastal plain.

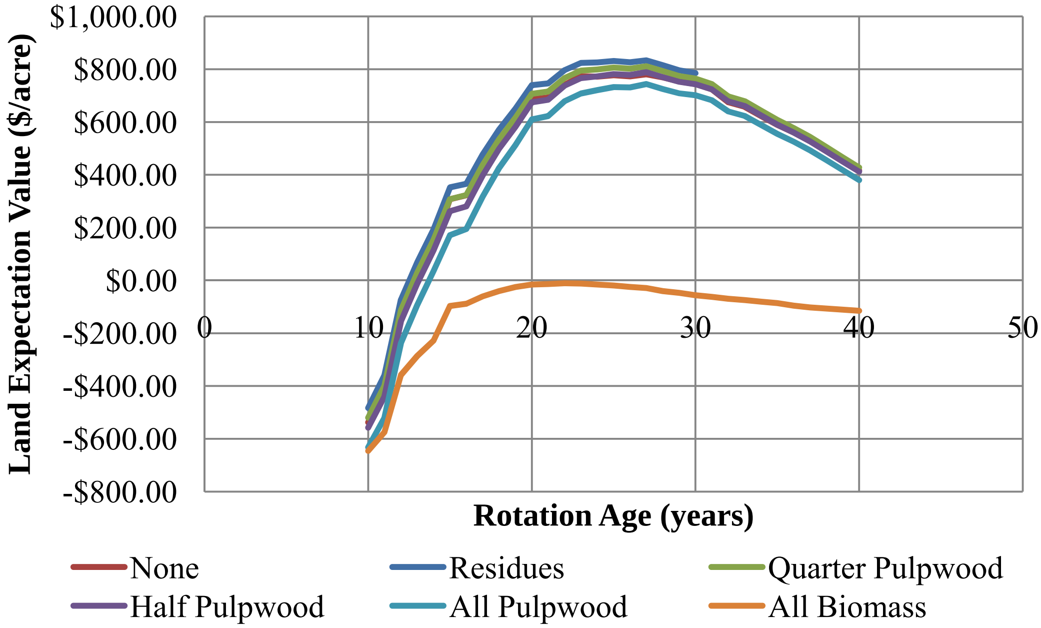

Figure 2-3. Land expectation values for six biofuel feedstock production scenarios in a slash pine plantation in the lower coastal plain, thinned at age 15.

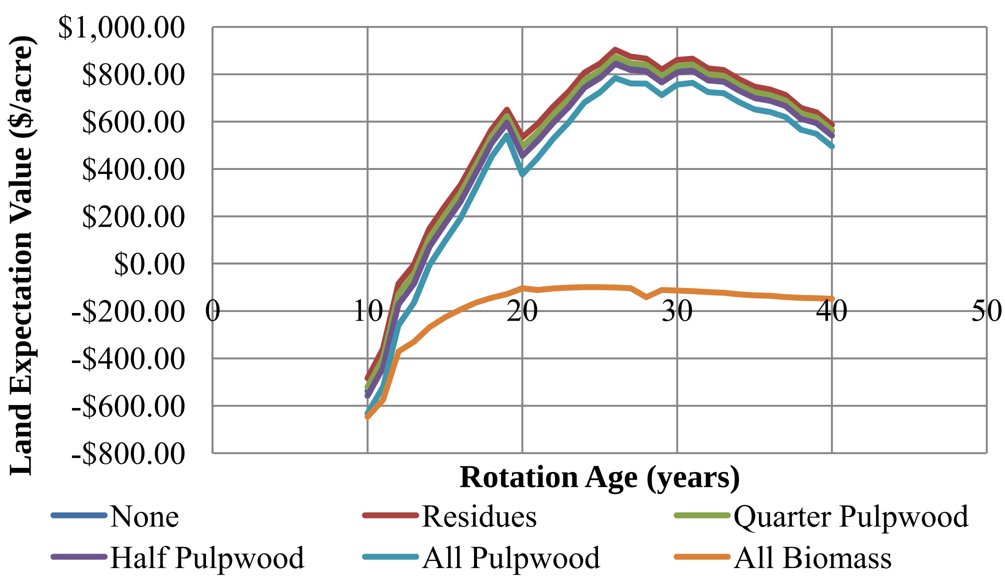

Figure 2-4. Land expectation values for six biofuel feedstock production scenarios in a slash pine plantation in the lower coastal plain, thinned at ages 12 and 20.

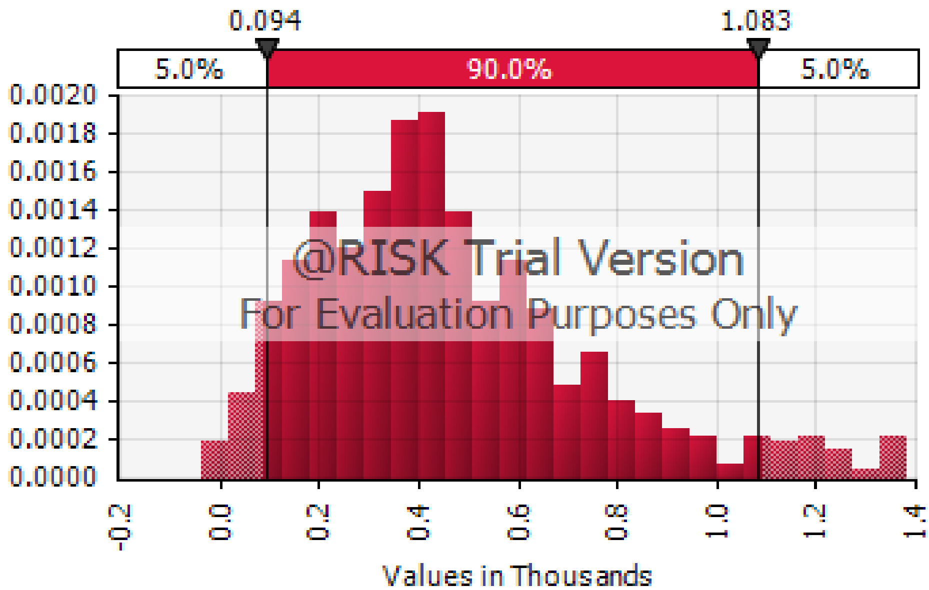

Figure 2-5. Probability distribution function for LEVs in an un-thinned stand.

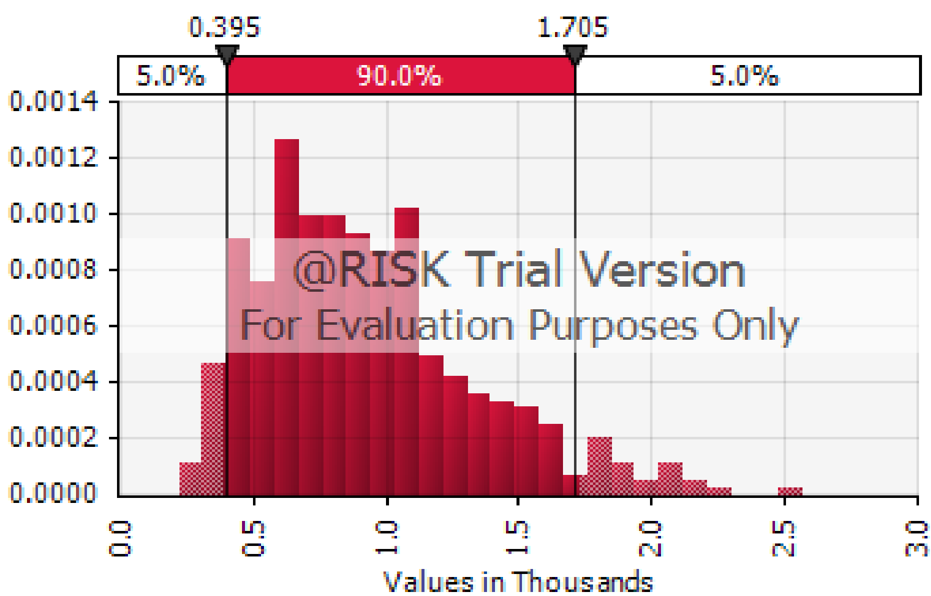

Figure 2-6. Probability distribution function for LEVs in stand thinned at year 15.

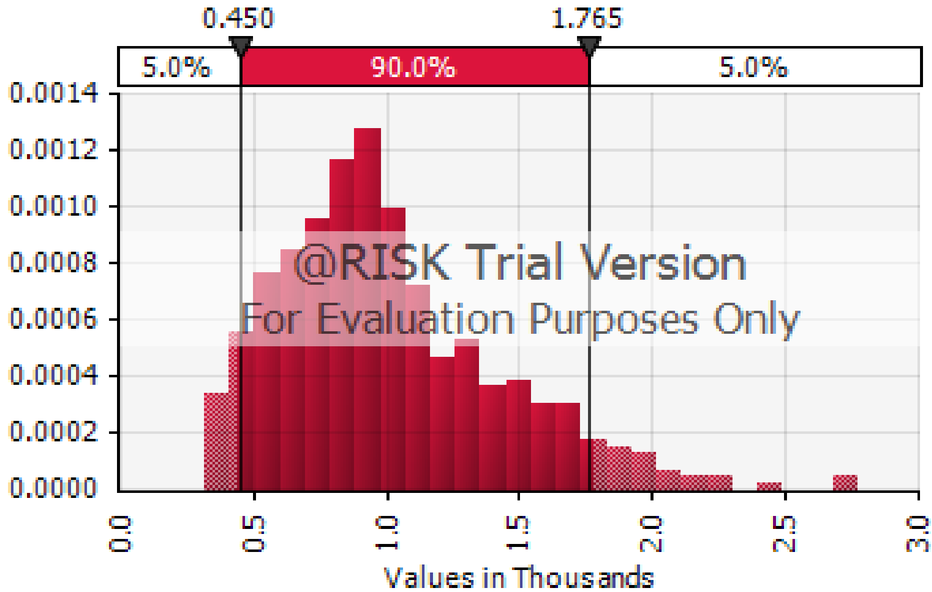

Figure 2-7. Probability distribution function for LEVs in a stand thinned in years 12 and 20.

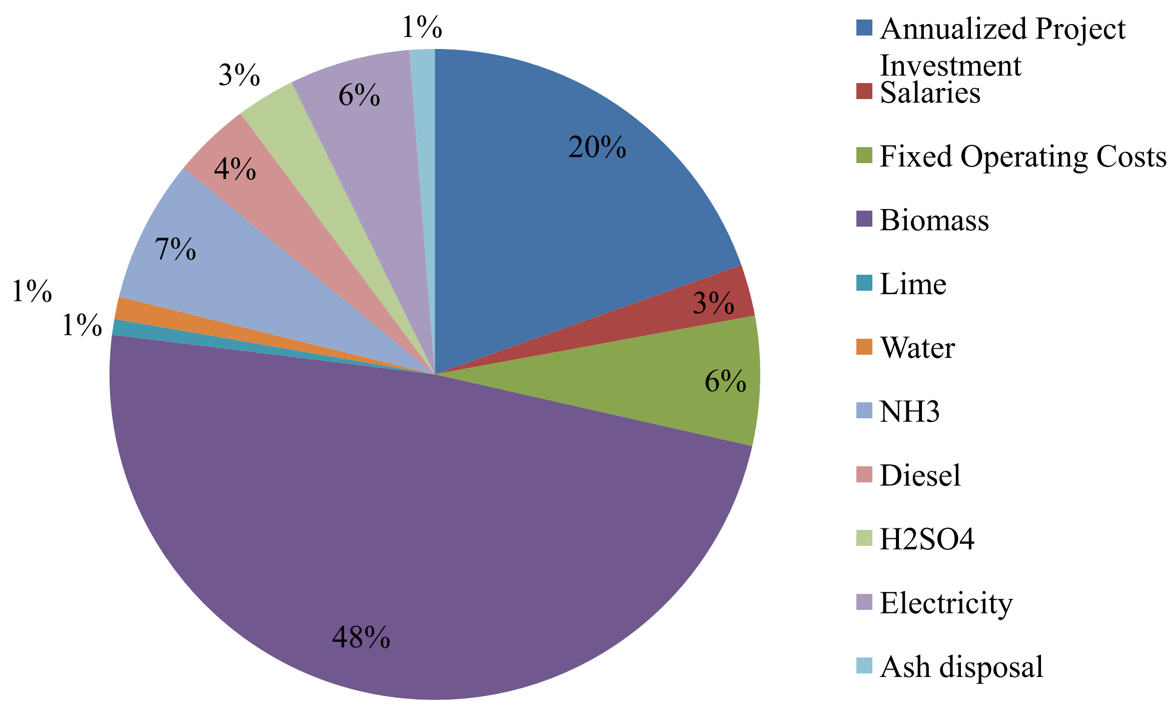

Figure 2-8. Components by percentage of unit production cost of ethanol.

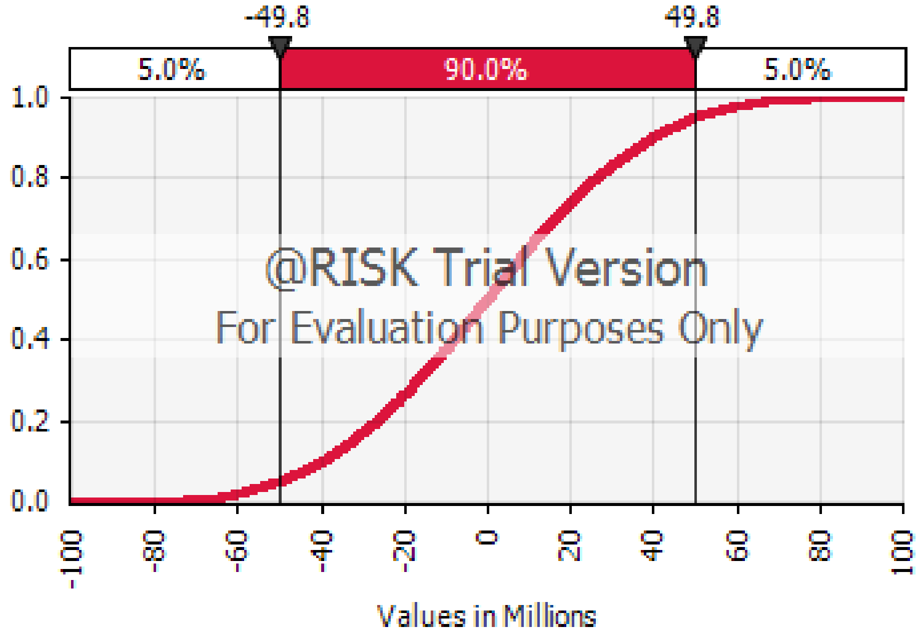

Figure 2-9. Cumulative probability distribution function for the unit production cost of ethanol from slash pine biomass.

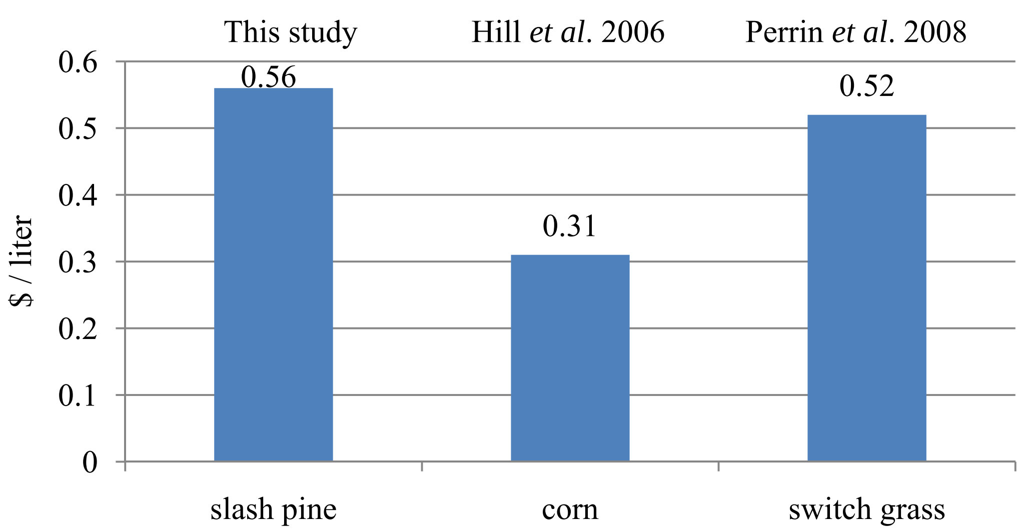

Figure 2-10. Unit cost of production of ethanol from slash pine, corn, and switchgrass.

CHAPTER 3
NET ENERGY BALANCE AND ENVIRONMENTAL IMPACTS OF ETHANOL PRODUCTION FROM FOREST BIOMASS

Introduction

Biofuels Energy Balance and Emissions Debate

The energy yield and environmental impacts of various biomass feedstocks for biofuel production have been researched and documented in many recent studies (Pimentel and Patzek 2005, Farrell *et al*. 2006, Hill *et al.* 2006). However, few studies have been conducted on forest biomass, particularly the southern pine plantations that represent such a vast resource of the region at over 30 million acres (Fox *et al*. 2004). According to the various assumptions and system boundaries determined by the researcher, the results of these studies have indicated mixed results. According to some studies, for instance, the net energy balance (NEB) of biofuels has ranged from less than one, indicating a greater input of energy than what is made available in the form of useful energy, to values as high as five and six (Pimentel and Patzek 2005, Schmer *et al*. 2008). This debate needs some clarification as a positive NEB greater than one is a fundamental criterion for the successful adoption of a given biofuel technology. Because NEB is a ratio of the energy outputs to the energy inputs, a successful energy technology must have a NEB greater than one simply to provide more energy than it takes to produce that same energy. The energy balance of ethanol from sugarcane has been reported at 3.24 and ethanol from switchgrass at 5.4 (Andreoli and De Souza 2006, Perrin *et al*. 2008). Similarly, the environmental impacts associated with the production and use life cycle of a particular energy source, with a specific focus on global climate change, is of paramount importance in assessing the wide spread long term sustainability of a developing energy source or technology. Of particular interest are the incorporation of land use changes and the consideration of associated emissions and impacts within the scope of analysis.

As reported by Fargione *et al.* (2008) and by Searchinger *et al.* (2008), land use is a significant factor when assessing the relative emissions of a biofuel production system. As more land is brought into cultivation for a given feedstock (e.g. corn for ethanol), further land use conversions are initiated in order to close the gap in supply and demand of the prior land use (e.g. soy beans), of the converted area. Scenarios like this lead to a situation in which potential environmental services such as carbon sequestration are forgone as land use is transformed from forested areas and other intact ecosystems to meet the increasing pressures on the land base. In this study, land use changes were considered to be negligible as the analysis is based on a multiple product output and the use of residues and undesirable small diameter trees from the currently forested area in the U.S. South. Thus, the assumption is that the current forest product industries requiring chip and saw and sawtimber size trees will not be impacted. Due to the limited impact on current forest products significant land use changes will not be necessary in order to close the gap between demand and supply for these products. The development of bio-refineries, facilities that integrate biomass conversion processes and equipment to produce fuels, power, and chemicals from biomass, represents one potential scenario that may alleviate any restriction of pulpwood supply. Co-locating the production facilities allows the more efficient use of resources by capitalizing on the outputs, or "waste stream," of one process and incorporating them into another.

Other Environmental Impacts

Although NEB and GHG emissions have been the primary focus of a majority of studies published on biofuel production, there are a multitude of applicable environmental impacts to be considered. Foremost among these are the potential acidification, eutrophication, ozone depletion, smog formation, ecotoxicity and human health impacts, carcinogenic and non-carcinogenic, associated with the life cycle processes of bioenergy production (Bare *et al*. 2003).

These impacts are not necessarily directly correlated, meaning that although GHG emissions may be reduced in comparison to an alternative fuel production life cycle, such as gasoline, nitrate emissions may be relatively greater for the process under consideration. In this scenario the global warming potential would be less, but the impact of eutrophication on the environment would be greater. Therefore, in order to determine the most environmentally favorable process, a subjective valuation, or weighting, of the various impacts is undertaken based on the relative importance or urgency of the given impacts considered. Based on the modeled impacts of current rates of GHG emissions, global climate change is generally considered as a primary environmental concern in recent studies (IPCC 2007).

Ethanol Conversion Technology

In the analysis of ethanol production from slash pine, there are various conversion technologies available for consideration, with multiple options at each stage of the conversion process including: pretreatment, conditioning, hydrolysis, fermentation, distillation, and product recovery. Each option, for every step of the ethanol production process, is at a varying degree of development, with associated costs and efficiencies. The process considered in this analysis consists of a dilute acid pretreatment, conditioning through over liming, simultaneous saccharification and fermentation through enzymatic hydrolysis, and molecular sieve distillation. This process is considered to be at the frontier of the technological development of cellulosic ethanol conversion and represents the most likely scenario for successful commercialization in terms of providing significant quantities of ethanol at prices competitive with starch based processes and gasoline. Specifically, the process design considered is presented as follows (Figure 3-1).

Life Cycle Assessment

In order to address the NEB and environmental impacts associated with the forestry operations, transportation steps, and conversion process required to produce and convert the feedstock to ethanol, the standard life cycle assessment (LCA) methodology was utilized. In this methodology, as defined within the International Organization for Standardization (ISO) 14000 series on environmental management, there are four major phases (Figure 3-2):

1. **Goal and scope definition:** describes the intended application, target audience, and model specifications of the study as well as determining the functional unit for analysis.

2. **Life cycle inventory (LCI):** based on the goal and scope, it determines the total amount of environmentally relevant resource use and emissions, according functional unit, and system boundaries of analysis.

3. **Life cycle impact assessment (LCIA):** classifies the data collected in the LCI phase according to the type of environmental impact they cause and characterizes the magnitude of those impacts.

4. **Interpretation:** process of assessing the raw data and impacts in order to draw conclusions and present results.

Goal and Scope Definition

The goal of this LCA is to identify the NEB, quantify the resource use, emissions, and associated environmental impacts in the categories of global warming potential, smog formation, acidification, eutrophication, ozone depletion, ecotoxicity, and human health, and to estimate the supply potential of ethanol production from Southern U.S. slash pine plantations in order to provide information about this particular energy production process for comparison with other conventional and alternative energy production pathways. The scope of the study includes the activities and processes within the seed orchard, nursery, plantation, ethanol mill, and four corresponding transportation steps between each of these stages and to the final pumping destination from the mill. The embodied energy of machinery and other chemicals and materials used is included in addition to direct energy (electricity, gas, diesel, and propane) inputs and material flows. Ethanol combustion in the vehicle is not included as the releases of this process will be the same for all ethanol produced regardless of the feedstock because once produced, all ethanol has the same chemical composition, and several studies have already been conducted identifying the differences in emissions of ethanol vs. gasoline (Nielsen and Wenzel 2005). Thus the main focus of this LCA is on the feedstock growth, harvest, and conversion phases in order to discern the merits and limitations between slash pine biomass and other potential ethanol feedstocks. The system will be analyzed according to the functional unit of 1000 L of ethanol produced and transported to the final pumping station (Figure 3-3).

Method

Life Cycle Inventory Stages

The LCI was conducted based on the sequential process of the ethanol production life cycle beginning with the seed orchard management and seed processing stage, followed by the transportation of seeds (TR – I), nursery management, transportation of seedlings (TR – II), plantation management and harvesting, transportation of the wood chips (TR – III), ethanol production, and transportation of the ethanol to the final pumping station (TR – IV) as shown in Figure 3-3. In each stage the material and energy flows were identified. Materials include chemicals, equipment, fuels, and water. Energy inputs include embodied energy and direct energy. The entire process is outlined in detail in Appendix B.

Net Energy Balance

The NEB was calculated by dividing the energy output associated with one functional unit by the sum of the total energy inputs for all stages to determine the ratio of output to input energy.

$$NEB = \frac{Eoutput}{Einput} \tag{3-1}$$

In order to calculate the total energy inputs for the life cycle stage, the quantity of direct energy inputs was multiplied by the energy content (MJ/L) of the fuel source and summed with the embodied energy inputs to give the total energy input per stage.

Embodied energy. This includes the amount of electricity (MJ) necessary to produce the machinery and materials consumed per functional unit in each step. The embodied energy of machinery was calculated by summing the embodied energy of each component, assuming a component weight ratio of each piece of equipment as given in Table 3-3. The embodied energy of each component was calculated by following values given in the (Hill *et al*. 2006). In order to allocate the use per functional unit produced, the total embodied energy of the machine was multiplied by the quotient of the hours of use per functional unit and the lifetime (hours) of the machine. The embodied energy of gypsum, a co-product of the ethanol production process, was also calculated per functional unit and allocated as an energy output in addition to the energy content of the ethanol produced. With the number of hours of use calculated for each piece of machinery and equipment, T, and the total energy used to produce the machine or equipment, also known as the embodied energy (EE), as calculated below:

$$EE = \sum_{i=1}^{n} \left(\frac{C_i}{W} * ee_i \right) \tag{3-2}$$

where C_i is the mass of component i (kg), W is the mass of the entire piece of equipment (kg), and ee_i is the energy required (MJ) to produce the component i as found in the literature. The embodied energy of each piece of equipment was allocated to one functional unit (EE_{FU}) by the following equation:

$$EE_{FU} = EE * \frac{T}{L} \tag{3-3}$$

where EE and T are as defined above and L is the lifetime of the equipment (hours).

Direct energy. These inputs include the electricity (MJ), diesel (L), gasoline (L), and propane (L) consumed in the processes of operating machinery and running equipment. Quantities are calculated per functional unit by determining the fuel used per seed, seedling, acre, or liters of ethanol, depending on the stage of the life cycle, per functional unit.

Life Cycle Impact Assessment

Emissions

In order to determine to what extent the processes of each life cycle stage contribute to the environmental impacts considered, the total emissions to soil, water, and air need to be calculated. There are several sources of emissions to consider in the analysis:

- Use of chemical fertilizers and other chemicals during the various stages of biomass growth and at the ethanol plant
- Electricity produced to manufacture these substances as well as the machines and equipment
- Emissions from the manufacturing processes of the machines and chemicals
- Emissions from the production and use of the direct energy inputs are subdivided into two categories of sources:
    - Emissions arising from the production of the energy source
    - Emissions associated with the combustion of the fuel on site[5]

In order to quantify the emissions for each of these sources and allocate them per functional unit, a combination of the database available from the LCA software SimaPro (http://www.pre.nl/simapro/default.htm) and data from the literature were used (Bare *et al*. 2003). The emissions from electricity production were based on the mix of the national electricity grid and associated emissions per MJ. Emissions due to manufacturing processes are

5 This is not true for electricity, however, because the emissions of electricity use occur at the power plant only, whereas diesel, gasoline, and propane incur emissions at the fuel production site and then again at the point of use.

given for all chemicals and machinery used in the system by SimaPro. Finally, emissions from the combustion of diesel, gasoline, and propane were found in the literature (Babbitt and Lindner 2005).

Embodied. The energy production process, assumed to be electricity that fuels the manufacturing produces emissions. These emissions were quantified with the use of the LCA software SimaPro, which contains a large database regarding the emissions of chemicals and materials.

Materials. This source of emissions stems from the leaching of fertilizers, herbicides, pesticides, and other chemicals, especially from the ethanol production stage, into the air, soil, and water. These emissions were quantified for each process stage by assuming some proportion of the applied substance is released into the environment beyond its target zone.

Direct. Once again, there are two sources of emissions in this category: those arising from the production of the energy source, and those associated with the use of the fuel on site. This is not true for electricity, however, because the emissions of electricity use occur at the power plant only, whereas diesel, gasoline, and propane incur emissions at the fuel production site and then again at the point of use. This data was obtained with the use of SimaPro and based on the quantities of the fuels used.

Tool for the Reduction and Assessment of Chemical and other environmental Impacts

In general, all emissions contribute to some extent to each impact category considered: global warming (kg CO_2 equivalent), acidification (moles H^+ eq.), eutrophication (kg N eq.), ozone depletion (kg CFC-11 eq.), smog formation (kg NO_x eq.), ecotoxicity (kg 2,4-D eq.) and human health impacts, both carcinogenic (benzene eq.) and non-carcinogenic (toluene eq.). In order to translate the emissions to the impact categories considered, the LCIA methodology known as TRACI 2 v 3.00 (Tools for the Reduction and Assessment of Chemical and other environmental Impacts) was used, which is also embedded within the SimaPro software. TRACI was developed by the U.S. Environmental Protection Agency to more accurately model the conditions within the U.S. as a majority of impact assessment models have been developed for European conditions. TRACI 2 v 3.00 allows the characterization of potential effects, including global warming, ozone depletion, acidification, eutrophication, tropospheric smog formation, eco-toxicity, human carcinogenic effects, and human non-carcinogenic effects.

Environmental impacts

Global warming. The impact category of global warming refers to the potential change in the earth's climate caused by the buildup of chemicals (i.e., "greenhouse gases") that trap heat from the reflected sunlight that would have otherwise passed out of the earth's atmosphere. Atmospheric concentrations of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) have climbed by over 30%, 145%, and 15%, respectively since the onset of the Industrial Revolution, causing net global climate change (IPCC 2007). Although "sinks" exist for greenhouse gases (e.g., oceans and land vegetation absorb carbon dioxide), the rate of emissions in the industrial age has been exceeding the rate of absorption. The Global Warming Potential (GWP) is expressed in terms of CO_2 for a time frame of 100 years. The final sum, known as the global warming index, indicates the potential contribution to global warming and is calculated as:

$$\text{Global Warming Index} = \sum m_i * GWP_i \tag{3-4}$$

where, m_i is the emission (in kilograms) of substance *i* and GWP_i is the global climate change potential of substance *i.*

Acidification. Acidification is a phenomenon resulting from processes that increase the acidity (hydrogen ion concentration, $[H^+]$) of water and soil systems. Changes in the alkalinity of lakes, related to their acid neutralizing capacity, are used as a diagnostic for freshwater systems analogous to the use of H^+ budgets in terrestrial watersheds. Acid deposition also has deleterious (corrosive) effects on buildings, monuments, and historical artifacts. The resulting acidification characterization factors are expressed in H^+ mole equivalent deposition per kilogram of emission and are dependent on the specific emission. Characterization factors take account of expected differences in total deposition as a result of the pollutant release location.

Eutrophication. Eutrophication is the fertilization of surface waters by nutrients that were previously scarce. When a previously scarce (limiting) nutrient is added, it leads to the proliferation of aquatic photosynthetic plant life. This may lead to a chain of further consequences, including foul odor or taste, death or poisoning of fish or shellfish, reduced biodiversity, or production of chemical compounds toxic to humans, marine mammals, or livestock. In general, the characterization factors estimate the eutrophication potential of a release of chemicals containing N or P to air or water, per kilogram of chemical released, relative to 1 kg N discharged directly to surface freshwater.

Ozone depletion. Stratospheric ozone depletion is the reduction of the protective ozone layer within the stratosphere caused by emissions of ozone-depleting substances. Recent anthropogenic emissions of chlorofluorocarbons (CFCs), halons, and other ozone-depleting substances are believed to be causing an acceleration of destructive chemical reactions, resulting in lower ozone levels and ozone “holes” in certain locations. Ozone depleting chemicals are dissociated by ultraviolet light, releasing chlorine atoms. The chlorine atoms act as a catalyst, and each can break down tens of thousands of ozone molecules before being removed from the stratosphere. These reductions in the level of ozone in the stratosphere lead to increasing ultraviolet-B (UVB) radiation reaching the earth, which has been identified as a carcinogen. The

Ozone Depletion Potentials (ODPs) are expressed in terms of CFC-11. The final sum, known as the ozone depletion index, indicates the potential contribution to ozone depletion:

$$\text{Ozone Depletion Index} = \sum m_i * ODP_i \qquad (3\text{-}5)$$

where, m_i is the emission (in kilograms) of substance *i* and ODP_i is the ozone depletion potential of substance *i*.

Smog. Nitrogen oxides (NO_x) and volatile organic compounds (VOCs) are emitted into the atmosphere from many natural and anthropogenic processes. In the atmosphere, these substances enter a complex network of photochemical reactions induced by ultraviolet light (UV-light) from the sun. These reactions lead to the formation of ozone (O_3), peroxyacetyl nitrate (PAN), peroxybenzoyl nitrate (PBN), and a number of other substances in the troposphere. The photochemical smog compounds degrade many materials and are toxic to humans, animals, and plants. The smog can be observed as a reddish brown cast in the air above many cities. In general, characterization factors estimate the smog formation potential of a release of chemicals in terms of NO_x.

Ecotoxicity. The ecological toxicity potential (ETP) has been developed as a quantitative measure that expresses the potential ecological harm of a unit quantity of chemical released into an evaluative environment. The goal of the ETP is to establish for life cycle inventory analysis a rank measure of potential ecosystem harm for a large set of toxic industrial and agricultural chemicals. The ETP is designed to capture the direct impacts of chemical emissions from industrial systems on the health of plant and animal species. In general, characterization factors estimate the eco-toxicity potential of a release of chemicals in terms of 2, 4-Dichlorophenoxyacetic acid.

Human health: cancer and non-cancer effects. The cancer and non-cancer human health impacts measure the potential of a chemical released into the environment to cause a variety of specific human cancer and no-cancer effects, respectively (Bare *et al*. 2003). The relative toxicological concern of an emission in the context of human health is currently calculated based on human toxicity potentials (HTPs). The HTP is an indicator used to compare the relative importance of toxic emission in situations where a site-specific risk assessment would be too expensive or data on the release sites is not always available (Hertwich *et al*. 2001).

Feedstock Supply

The total quantity of ethanol producible on an annual basis was calculated, as well as the equivalent amount of gasoline the ethanol could displace. The total feedstock supply was calculated based on a steady state basis. That is, assuming that there is an equal amount of forestland planted in each year, and thereby providing an equivalent amount of biomass each year. The size class proportions were considered and expanded to include the entire acreage of slash pine in the U.S. South. Thus, by knowing the biomass yielded from thinning operations at year 15 and harvest at year 25 and the total number of acres present, the number of acres in the year 15 and 25 age groups can be determined, as well as the annual biomass yield. Based on the yield and the conversion rate to ethanol, the total annual production quantity of ethanol is calculated. In order to determine the total amount of gasoline that can be displaced by the annual ethanol production, the differing energy contents of the fuels must be taken into consideration (23.5 MJ/liter for ethanol versus 34.8 MJ/liter for gasoline), as it takes about 1.48 liters of ethanol to travel the same distance as possible with 1 liter of gasoline. Finally, the supply potential is determined by extrapolating to all pine species in the U.S. South, assuming that management and yield are similar across the region for various pine species.

Results

Material Use

The total material use was calculated for the system based on each life cycle stage. Results are given below for each of the major categories considered of chemicals (Table 3-3), equipment (Table 3-5), fuels (Table 3-6), and water (Table 3-7). The later stages of the process, including the plantation and ethanol mill were found to be responsible for a majority of the material use in the system. This is due to the increased proportion of activities at these later stages contributing towards one functional unit. For instance, while the required number of seed requires only fractions of an acre at the seed orchard, the area required for one functional unit's worth of biomass at the plantation is much greater.

Net Energy Balance

Results include the net energy balance, which was calculated in the Method section of this chapter, above. The final NEB was determined to be 5.67. Of the contributions to the inputs, the percentage of each lifecycle stage is given below (Figure 3-5). The direct energy use and embodied energy use each contributed to 74% and 26% of the total energy input, respectively. Of the direct energy use electricity, diesel, propane, and gasoline each contributed 77.54%, 22.38%, 0.08% and 0.00% to the total, respectively. Of the embodied energy inputs equipment, chemicals and water contribute 25.17%, 65.14%, and 9.70% respectively.

Impact Assessment

The impact assessment was conducted based on the emissions from the system calculated as described above in the Method section of this chapter. The total impacts for the categories considered are given for each stage of the life cycle in Table 3-8 below. The non-cancer human health impact was the greatest magnitude of all. Cancer human health impacts, eutrophication, ozone depletion, and smog formation were all found to be minimal. The ethanol mill and fertilization at the various stages of biomass growth were found to be the significant contributors to the impacts of the process.

Feedstock Supply

Based on the analysis, there is enough feedstock available on an annual basis supplied from thinning and harvest residues and pulpwood sized trees to produce 1.7 billion gallons of ethanol. This is equivalent to 1.2% of the annual gasoline use in the U.S. When these results are extrapolated out to the entire Southern region, including the states of Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, South Carolina, Tennessee, Texas (East), and Virginia, there is enough biomass available to produce 5.5 billion gallons of ethanol, equivalent to 4% of annual gasoline use in the U.S.

Conclusions

The results of the analysis demonstrate the potential of slash pine biomass as a feedstock for cellulosic ethanol production due to the relatively high NEB, limited environmental impacts, and potential impact on energy supply. The NEB for the process under consideration is competitive with other biofuels being discussed as shown in Figure 3-9. Further improvements in conversion technology, such as advancement of cellulase enzyme production and fermentation technology, locating mills near to plantations, and increasing plant output may also increase the efficiency of conversion and the viability of the fuel source. Along with the efficiency of the process, the implications to land use change may also be significant, such as increasing the acreage under pine plantation management. As the demand for biofuel rise and the efficiency of production from forest biomass increases, there may be a higher use of land associated with forestry and biomass production. Furthermore, as bioenergy becomes a profitable venture for Southern NIPF owners, management objectives may change, such as decreasing rotation lengths and increasing planting densities. Limitations to the study include the assumptions made regarding the ethanol production process, particularly at the stage of conversion. In particular, the use of cellulase enzymes in the conversion process is assumed to be purchased from an off-site source, but co-location of enzyme production facilities and ethanol conversion facilities may be a more realistic future scenario. Generally, the data available regarding the enzymatic hydrolysis process are scarce and guarded as trade secrets. As the process continues to be commercialized and developed, data will likely be made more widely available for more accurate analysis. Further research into these areas would ease the restrictions on the model, and increase the robustness of the analysis. Further considerations of the model include the identification of the benefits and drawbacks of multiple feedstocks and conversion technologies, as well as potential developments towards centrally located bio-refineries. Given the overall NEB and potential for fuel production, it is clear from this study that cellulosic ethanol may play an important role in the future development of the forestry markets of the U.S. South.

Table 3-1. Required output from each stage to produce one functional unit.

	Output	Units	Quantity	Acres	Kilometers
Seed orchard	Seeds	Number	118.66	2.54E-4	
TR – I	Delivery	Kgs	0.00		321.87
Nursery	Seedlings	Number	98.89	1.23E-4	
TR – II	Delivery	Kgs	3.14		160.93
Plantation	Chipped biomass	Green tonnes	5.27	1.12E-1	
TR – III	Delivery	Green tonnes	5.27		160.93
Ethanol mill	Ethanol	Liters	1000.00		
TR – IV	Delivery	Liters	1000.00		321.87

Table 3-2. Composition of equipment used by component percentage.

Equipment	C steel	Al	Cu	Zn	Plastics	Rubber	Total weight (kg)
Ford 3910 Tractor	70.00	8.00	3.00	1.00	8.00	10.00	2041.00
Ford 7610 Tractor	70.00	8.00	3.00	1.00	8.00	10.00	3220.00
OGM Tree shaker	70.00	8.00	3.00	1.00	8.00	10.00	10000.00
Dryer	80.00	0.00	0.00	0.00	10.00	10.00	250.00
De-winger	100.00	0.00	0.00	0.00	0.00	0.00	250.00
Cleaner	100.00	0.00	0.00	0.00	0.00	0.00	250.00
Size sorter	100.00	0.00	0.00	0.00	0.00	0.00	250.00
Weight sorter	100.00	0.00	0.00	0.00	0.00	0.00	250.0
Irrigation Equipment	0.00	100.00	0.00	0.00	0.00	0.00	1000.00
TigerCat 726 Feller Buncher	70.00	8.00	3.00	1.00	8.00	10.00	12765.00
TigerCat 630C Skidder	70.00	8.00	3.00	1.00	8.00	10.00	17010.00
TigerCat 234 Delimber/Loader	70.00	8.00	3.00	1.00	8.00	10.00	14850.00
Morbark NCL 234 Chipper	70.00	8.00	3.00	1.00	8.00	10.00	12353.00
Refrig. Semi-Truck and Trailer	70.00	8.00	3.00	1.00	8.00	10.00	13000.00
Semi-Truck and Trailer	70.00	8.00	3.00	1.00	8.00	10.00	13000.00
Semi-Truck and Tanker	70.00	8.00	3.00	1.00	8.00	10.00	13000.00

Table 3-3. Chemical use at the seed orchard, nursery, and plantation stages (kg) per functional unit.

	Fertilizers			Herbicides	Pesticides	Fungicides	Fumigant
	N	P	K	2, 4 – D	Malathion	Atrazine	Methyl Bromide
Seed Orchard	0.01	0.00	0.00	2.9E-5	3.1E-5	0.00	0.00
Nursery	0.01	0.01	0.00	4.0E-4	2.6E-4	0.00	0.02
Plantation	8.34	2.90	2.74	3.8E-3	1.9E-2	0.00	0.00
Total	8.36	2.91	2.75	4.2E-3	1.9E-2	0.00	0.02

Note: The amounts are given for the proxy chemical available in TRACI. N (ammonium nitrate), P (diammonium phosphate), K (potassium chloride), herbicides (2, 4 – Dichlorophenoxyacetic acid), pesticides (Malathion), Fungicides (Atrazine), Fumigant (methyl bromide)

Table 3-4. Chemical use at the ethanol mill (kg) per functional unit.

Sulfuric Acid	Lime	Inorganic Chemicals	P
1.16	76.56	220.99	5.21

Note: Inorganic chemicals include clarifier polymer, cellulose enzymes, wastewater chemicals, wastewater polymer, boiler chemicals, and cooling tower chemicals.

Table 3-5. Equipment use (kg) throughout the life cycle per functional unit.

	C Steel	Al	Cu	Zn	Plastics	Rubber	Stainless Steel	Concrete
Seed Orchard	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TR – I	18.31	2.09	0.78	0.26	2.09	2.62	0.00	0.00
Nursery	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TR – II	9.15	1.05	0.39	0.13	1.05	1.31	0.00	0.00
Plantation	1.27	0.14	0.05	0.02	0.14	0.18	0.00	0.00
TR – III	9.15	1.05	0.39	0.13	1.05	1.31	0.00	0.00
Ethanol Mill	0.33	0.00	0.00	0.00	0.00	0.00	0.21	5.00
TR – IV	18.31	2.09	0.78	0.26	2.09	2.62	0.00	0.00
TOTAL	56.52	6.42	2.41	0.80	6.42	8.03	0.21	5.00

Table 3-6. Fuel use (MJ) throughout life cycle per functional unit.

	Propane	Gasoline	Diesel	Electricity
Seed Orchard	0.01	0.00	0.01	0.10
TR – I	0.00	0.00	0.00	0.00
Nursery	0.00	0.00	0.04	9.88
TR – II	0.00	0.00	0.04	0.00
Plantation	0.00	0.02	28.46	0.00
TR – III	0.00	0.00	64.44	0.00
Ethanol Mill	0.12	0.00	0.00	17517.08
TR – IV	0.00	0.00	18.30	0.00
TOTAL	0.13	0.02	111.29	17527.06

Table 3-7. Water use (L) throughout life cycle per functional unit.

Seed Orchard	0.12
TR – I	0.00
Nursery	835.01
TR – II	0.00
Plantation	25.47
TR – III	0.00
Ethanol Mill	1374.60
TR – IV	0.00
TOTAL	2235.20

Table 3-8. Environmental impacts associated with each life cycle stage.

	GWP	Acid.	Eutr.	Ozone	Smog	ETP	HHC	HHNC
Equivalent	Kg CO2	H+ moles	Kg N	Kg CFC -11	NOx	2,4 –D	Benzene	Toluene
Seed Orchard	0.00	0.00	0.00	7.4E-13	0.00	0.00	0.00	0.00
TR – I	18.76	6.42	0.02	2.9E-06	0.07	5.42	0.04	155.25
Nursery	0.01	0.00	0.00	1.2E-09	0.00	0.00	0.00	0.07
TR – II	9.38	3.21	0.01	1.4E-06	0.03	2.71	0.02	77.62
Plantation	324.40	111.02	0.30	5.0E-05	1.17	93.65	0.61	2684.62
TR – III	192.79	65.98	0.18	3.0E-05	0.70	55.66	0.36	1595.50
EtOH Mill	1561.11	534.24	1.44	2.4E-04	5.65	450.69	2.94	12919.18
TR – IV	51.37	17.58	0.05	7.9E-06	0.19	14.83	0.10	425.11
TOTAL	2157.82	738.44	2.00	3.3E-04	7.81	622.96	4.07	17857.34

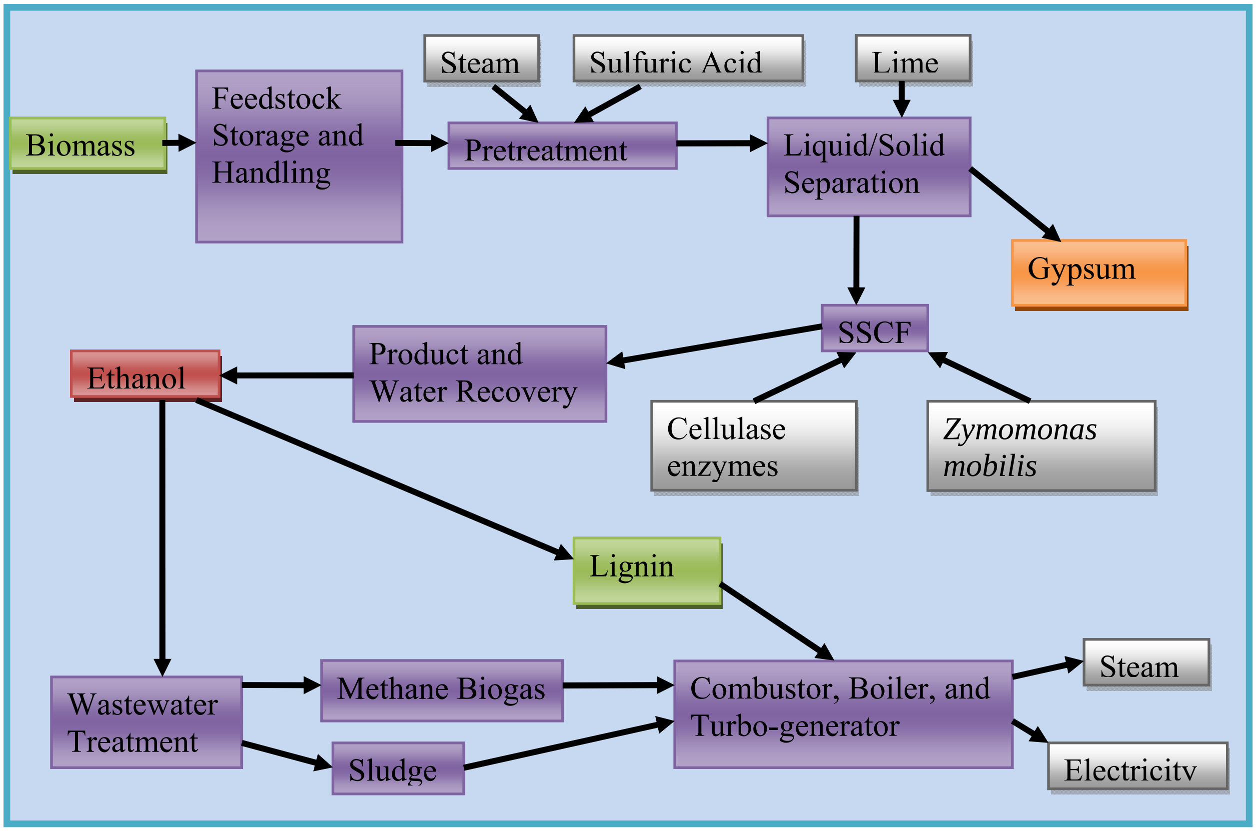

Figure 3-1. System flow diagram of enzymatic hydrolysis ethanol production process.

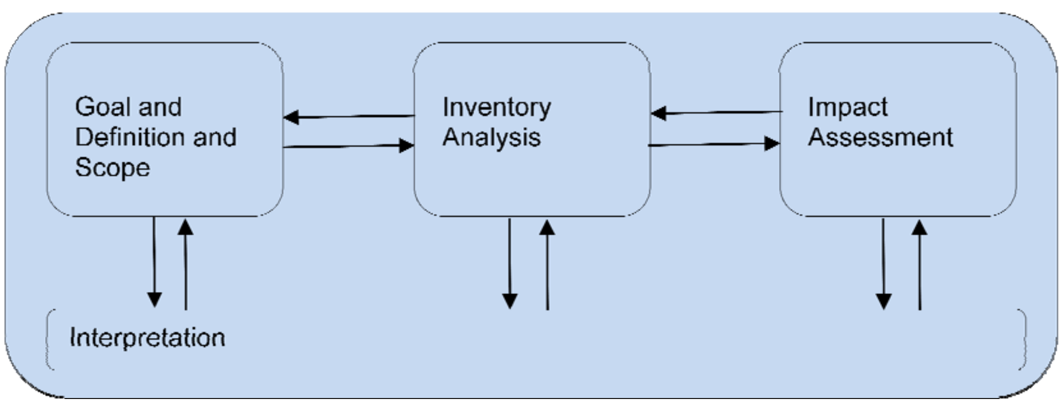

Figure 3-2. Components of life cycle assessment methodology.

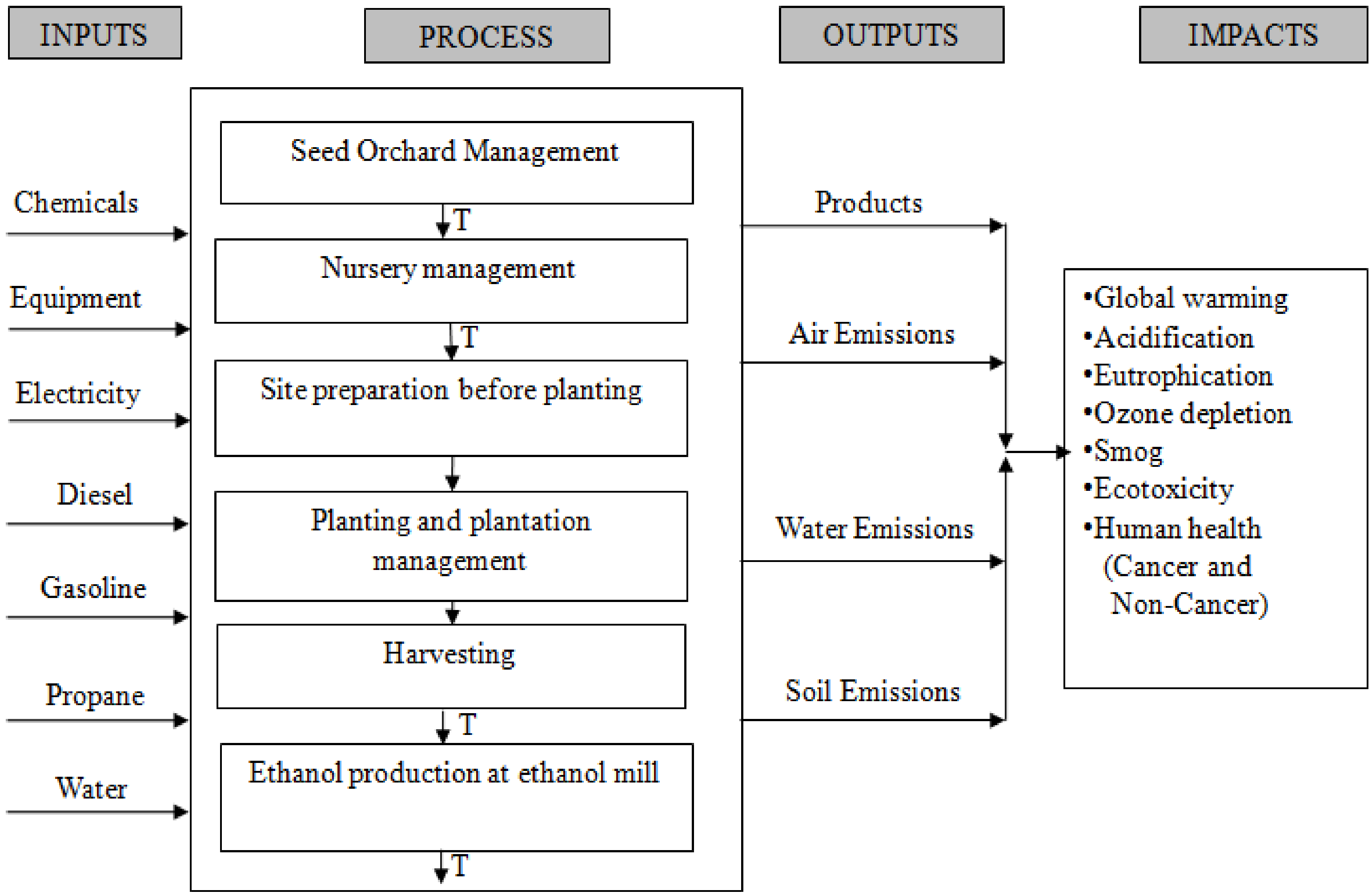

Figure 3-3. System considered for analysis in LCA.

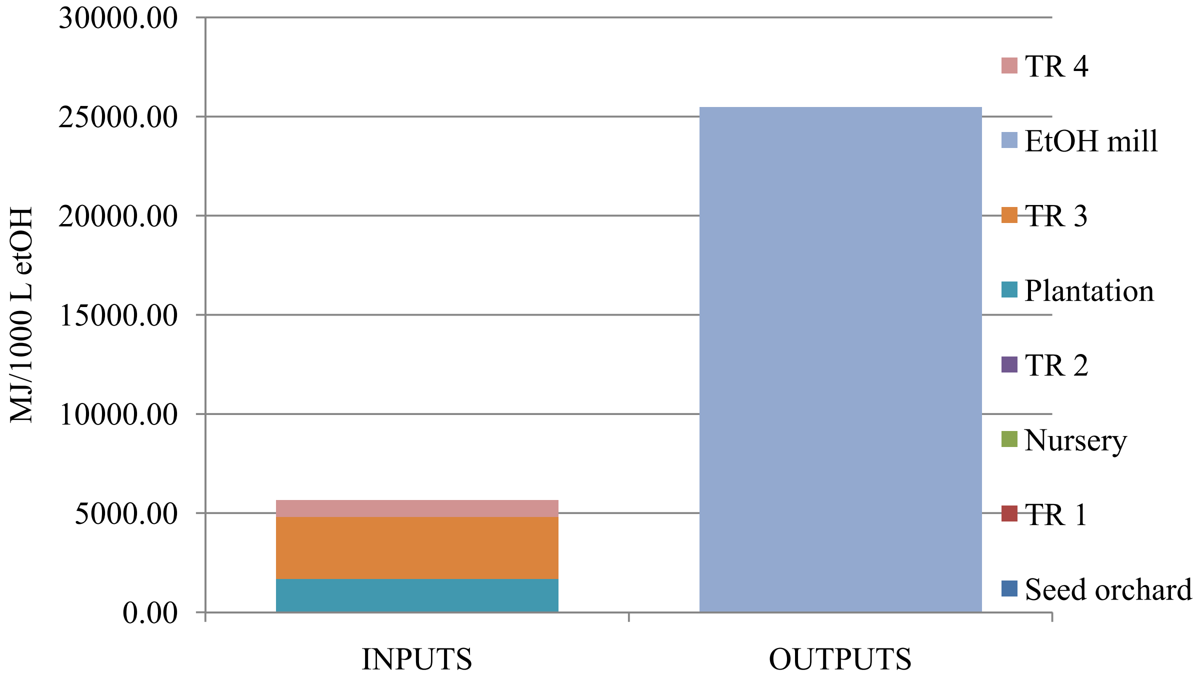

Figure 3-4. Energy inputs and output magnitude by life cycle stage.

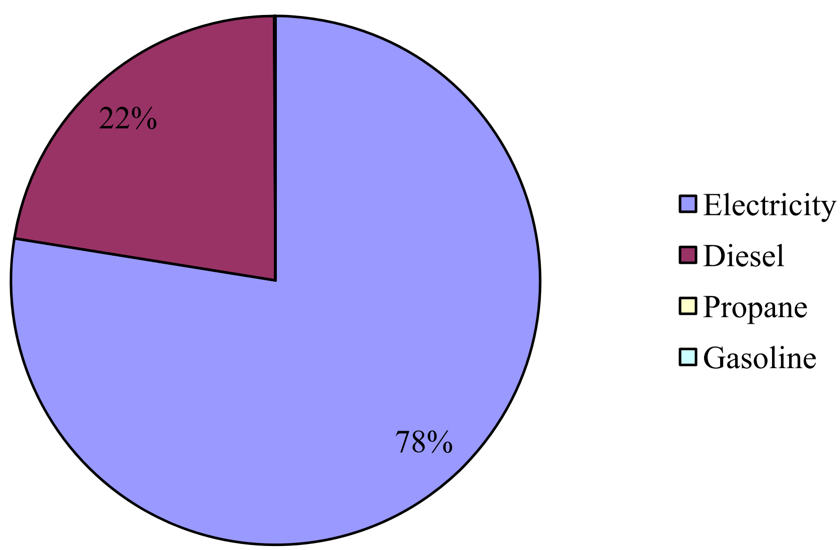

Figure 3-5. Energy inputs by fuel type for the ethanol production life cycle.

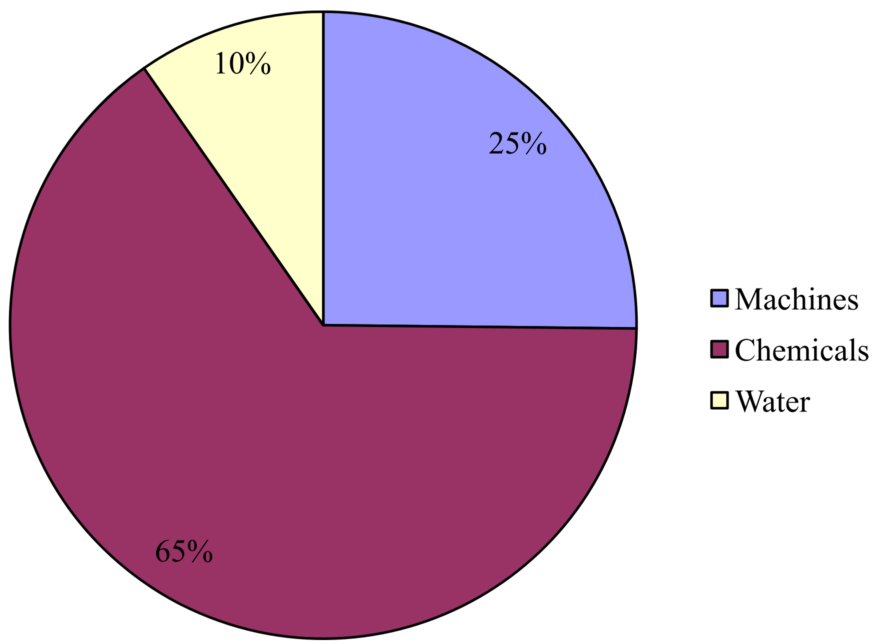

Figure 3-6. Energy inputs and outputs of ethanol production life cycle by type.

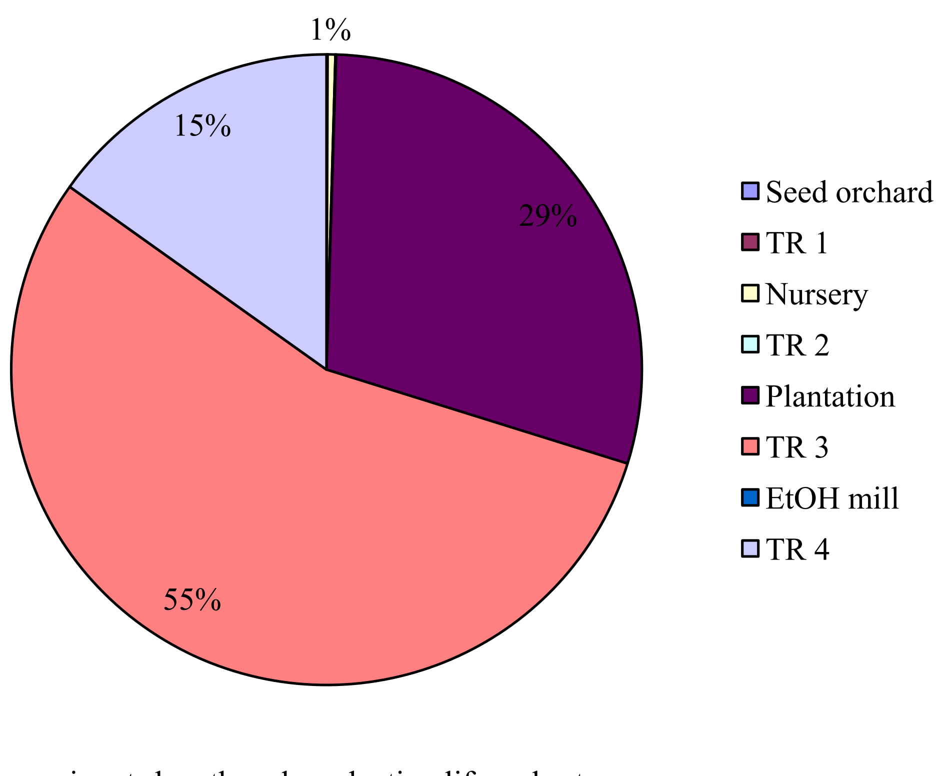

Figure 3-7. Energy inputs by ethanol production lifecycle stage.

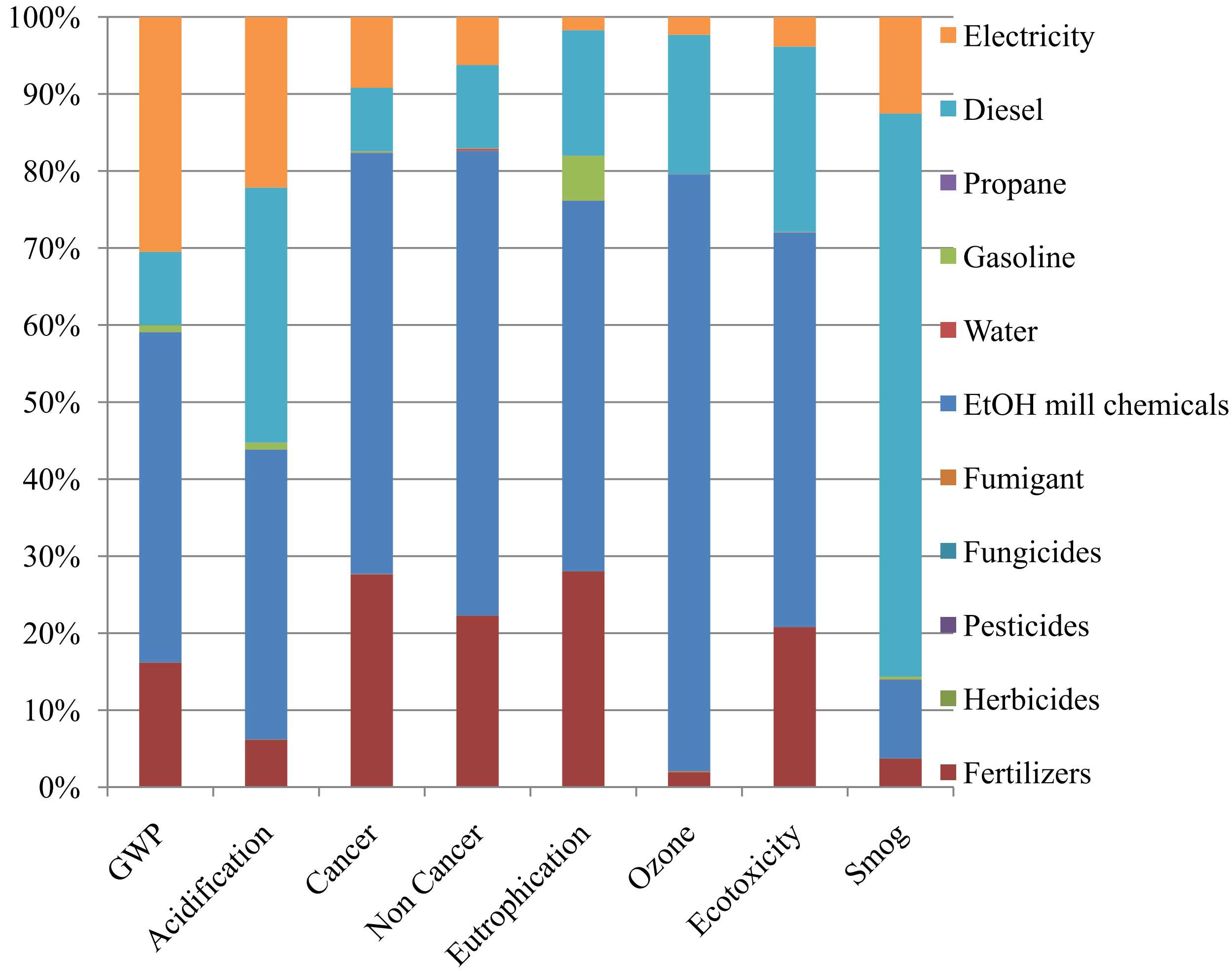

Figure 3-8. Environmental impacts by source of emission for the ethanol production life cycle.

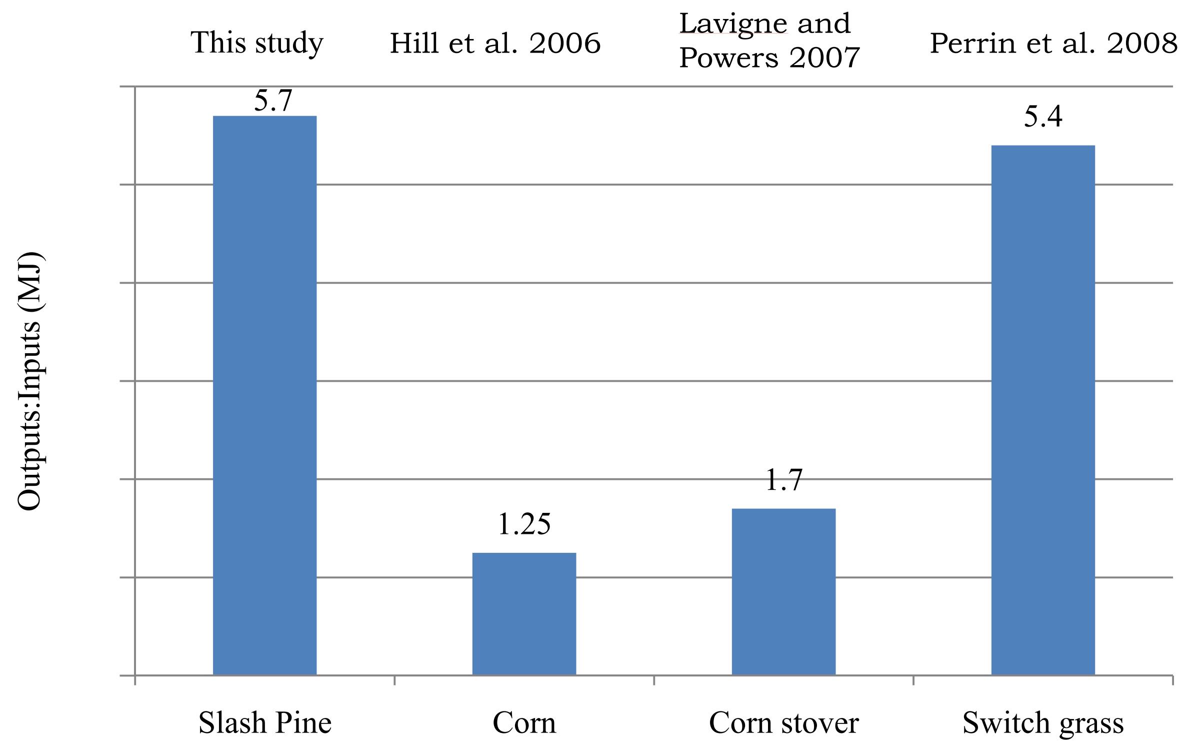

Figure 3-9. Published net energy balances of slash pine, corn grain, corn stover and switchgrass.

CHAPTER 4
SUMMARY AND CONCLUSIONS

Summary of Results

The results presented in this study supply information critical to the bioenergy development in the U.S. The focus of the second chapter was on the economics of ethanol production from slash pine. This included the profitability to the forest owner as well as the competitiveness of the cost of production. The third chapter focused on the energetic and environmental impacts of the production process. Overall, cellulosic ethanol production appeared to be a potentially rewarding venture for Southern forest owners.

Economics of Ethanol Production from Forest Biomass

The results demonstrate that ethanol produced from slash pine biomass grown on Southern NIPF lands and sold to the market at current biomass stumpage rates is a relatively profitable enterprise for NIPF owners in the U.S. South. As demand for biofuels continues to increase, the value of harvest residues and other forest biomass may also rise, leading to a greater profit for the forest owner. Also, as carbon trading develops as a tool for mitigating the effects of climate change, forest owners may profit additionally by serving as carbon bankers in this developing market due to the avoided GHG emissions of ethanol produced from slash pine biomass as opposed to petroleum based gasoline. Increased forestland values have many associated implications for forestland management, health, and ecosystem services. The increased profitability of these lands will allow forestry and related activities and amenities to be continued as a viable land use option by small private landowners. Therefore, the use of small diameter trees and harvest residues for biofuel production is likely to contribute towards maintaining lands in forestry rather than conversion to other uses. While this is beneficial in terms of the positive impacts associated with forestry, it is also possible that there will be associated negative impacts of forest biofuel production, particularly in terms of markets competing for the small diameter biomass. Specifically, the pulp and paper industry may find itself in competition with ethanol producers for their raw material feedstock. The forest industries associated with higher value products, such as sawtimber, are less likely to be impacted by a developing Southern biofuel industry.

While the favorable economic conditions for growth, harvest, and sale of biomass from the forest owner perspective may be helping to accelerate the cellulosic ethanol industry, the relatively higher cost of production per unit continues to be a stumbling block for the fledgling industry. The cost of production must fall in order to be competitive with ethanol produced from corn grain and sugarcane, and with gasoline. However, as oil prices continue to rise, the gap is narrowed. Also, as technological development advances and conversion efficiency and yields continue to increase, the unit cost of ethanol produced from Southern pine plantation biomass may decrease further. Other factors that may contribute to the relative feasibility of this ethanol source include varying plant locations, production capacities, and co-location with associated industries. Furthermore, in light of the advantages associated with a domestic renewable fuel source, the government may provide greater incentives for production such as the $1.01 per gallon tax credit recently offered in the 2008 Farm Bill.

The distributional impacts of an increase in ethanol production appear to be favorable as much of the revenues would be circulated in rural areas, enhancing the domestic economy. The possibility to develop domestic bio-refining industries would have significant ripple effects, including greater production of fuel and chemicals, including resins, dyes, and pharmaceuticals, domestically. This production would offset current imports, impacting the national balance of trade. Overall, the economics of cellulosic ethanol production from Southern NIPF slash pine plantations, and likely other pine species as well, appears to hold a great potential for development of bioenergy and other biobased products as well.

Energetic Yield and Environmental Impacts

The results from the LCA primarily demonstrate the relatively energy efficient process of ethanol production from slash pine plantations. The high NEB and potential production supply indicate that pine based ethanol may provide a major source of transportation fuel for the nation. There are important environmental impacts associated with the life cycle of the ethanol production process, and the majority of the impacts were associated with the ethanol mill stage itself. The emissions from machine and chemical manufacture as well as the fertilization at three biomass growth stages were also found to contribute significantly to the total system impacts. The significant environmental impacts of the system include eco-toxicity, acidification, non-cancer human health, and global warming. GHGs were primarily emitted from the consumption of diesel and other fuels, and the emissions associated with the ethanol conversion process. The growth of the plantation sequesters carbon dioxide from the atmosphere. The amount sequestered is difficult to calculate accurately due to uncertainties in carbon sequestration rates in the soil and percentage of root biomass to total tree biomass. It does appear that there is potential for soil carbon sequestration through pine plantation growth, but appropriate post harvest and pre planting activities would be critical for not disturbing the soil and releasing the sequestered carbon. Improvements in conversion efficiency would also help to minimize the impacts of the process. Improvements can also be made during the biomass production phases of the life cycle. The multiple applications of toxic pesticides at the seed orchard, nursery and plantation aim to increase per acre yield, but also lead to many emissions responsible for midpoint impacts like eco-toxicity. It is unclear what impact ethanol production will have on land use in the U.S. South. While rising populations are putting increasing amounts of pressure on forests to meet demands on less area, the increased opportunity cost of converting forestlands due to the value of biofuel production may lead to more lands being managed as forestry operations.

Although forest biomass will not replace oil and fossil fuel use, it will play a significant role in the primary energy supply as a portion of a sustainable energy matrix. The use of forest biomass will likely be central to achieving the targets set out by the government's latest legislation. Due to the emphasis placed on the importance of cellulosic ethanol production by policy makers and the overall potential from Southern pine plantations, NIPF owners may be considered for targeting government incentives such as subsidies and rebates.

Limitations to the Study

Although the study attempted to be relatively comprehensive in the scope of ethanol production from Southern pine plantations, many limitations to the breadth and depth of the analyses remain. For instance, the economic indications of the study do not include any non market values associated with the existence or aesthetics of the forest, but only those values representative of current conditions of Southern pine plantation NIPF owners. Also, the scope is limited to the forest owner and ethanol producer. Although a few potential impacts are discussed, a complete input-output analysis would provide more insight into the economics of ethanol production. 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. As alternative fuel sources play an increasingly important role in meeting the demand for energy, the government will likely continue to offer various incentives to encourage the production of biofuels.

The energetic and environmental impacts associated with the process may also change depending on the species of feedstock and depending on the final output. The study of alternative species and energy production scenarios would provide greater insight. For instance, how loblolly pine (*Pinus taeda*) growth for electricity generation may compare with slash pine growth for ethanol production is not clear from the current analysis. Limitations in the data available regarding the cellulosic ethanol conversion process technology also prevent more highly specific numbers regarding yield per kg biomass and material use at the mill from being calculated. As this process becomes more commercialized, the data will likely become more standardized.

Although these analyses provide a thorough investigation of the questions at hand, they are limited by the information available. For instance, neither non market values, nor broader economic impacts (or "ripple effects") are considered in the analysis, limiting the scope of the research. While the study does incorporate the energy and materials necessary for production and use of infrastructure required during the production lifecycle, consideration of impacts such as land use change is not included.

Future Work

Based on the limitations discussed above, future work would include expanding the analysis to consider similar plantation species of the Southern forests. Also, alternative conversion techniques may prove to have varying degrees of success regarding NEB and environmental impacts. Any future work would incorporate alternative species and conversion technologies. In addition to the species selected, the management of the forest stand would change the energetic and economic yields. If shorter rotations were considered or if coppicing hardwoods were analyzed, these results would likely be significantly altered. Also, the economic implications of carbon sequestration could be more fully addressed in further work. Incorporating carbon offset credits at the ethanol mill may provide new perspective on the costs of production. Overall, while this study answered many questions regarding the potential of ethanol production from forest biomass, much work remains to be completed in this area to help guide our path towards a sustainable energy future.

APPENDIX A
TWO-STAGE DILUTE SULFURIC ACID CELLULOSIC ETHANOL PRODUCTION PROCESS DESCRIPTION

This technique is a two step procedure targeted at hydrolyzing hemicelluloses and cellulose, respectively.

Prehydrolysis

The first stage of the process is conducted under more mild conditions to maximize yield from hemicellulose, which more readily hydrolyzes than cellulose. Washed and milled wood chips are treated using a 0.5% acid at temperatures of 392°F (200°C) to separate the pentose (C5) sugars for fermentation to ethanol and distillation.

Hydrolysis

The second stage is optimized to hydrolyze cellulose, and thus is operated under more concentrated acid and higher temperatures. The remaining solid cellulose and lignin from the prehydrolysis is treated with a 2% acid in liquid at 464°F (240°C) and the remaining sugars are fermented and distilled (California Energy Commission 2008).

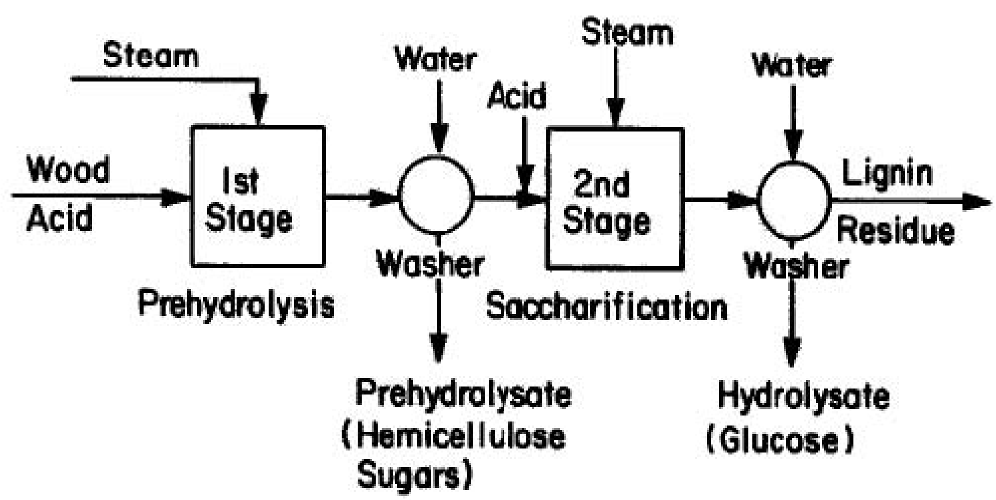

Figure A-1. Simple flow diagram of the two-stage dilute sulfuric acid hydrolysis process (Harris *et al* 1985).

APPENDIX B
LIFE CYCLE INVENTORY STAGES OF ETHANOL PRODUCTION FROM SLASH PINE

Seed Orchard Management and Seed Processing

The scope of this analysis begins with the collection of seeds at the seed orchard. This stage includes two phases: management of the seed orchard and seed processing. Seed orchard management includes mowing, fertilization with nitrogen (N), phosphorous (P), and potassium (K), herbicide applications of Goal® and Fusilade®, and pesticide applications of Asana® and chlorpyrifos. These activities are all conducted with the use of a diesel tractor and necessary attachments.

The seed collection and processing phase begins with the shaking loose of cones from the trees into bins by a mechanical shaker. Cones are then transferred in the bins to the seed processing area, where they are loaded on to trays, stacked and dried with propane gas vented through aluminum ducts via an electric fan. After an initial drying of 24 hours to 15% moisture the cones open and the seeds are released and collected from the bottom of the trays. The seeds are then transferred to bins and filtered through screen to separate out other materials. Next the seeds are placed into the de-winger, which uses a shaking motion to remove the outer wings of the seeds, which is followed by a sorting by size and gravity sorting designed to separate out the sterile seeds or "pops." Finally, the seeds are dried further to 6% moisture and are stored in corrugated cardboard cylinders for transport to the nursery.

Transportation of Seeds to Nursery (TR – I)

The seeds are transported in a diesel fueled refrigerated semi-box trailer, or "reefer," from the seed orchard and processing facility to the nursery.

Nursery Management

Once delivered to the nursery the seeds undergo the process of stratification, which aims to simulate the natural conditions seeds endure prior to germination. Upon arrival, the seeds are stored in a cooler at 40°C for 10 days. Following storage the seeds are removed and submerged in water for 12 hours. After soaking, seeds are returned to the cooler at 40°C for 14 days. Upon removal from the cooler, seeds are bathed in a dual treatment of the fungicide Bayleton® and pesticide thiram to protect the seedlings from fusiform rust and predation by birds, respectively. After the chemical treatment, the seeds are once more stored in the cooler at 40°C for 10 days prior to planting. Preparing the ground and seed beds for planting is an intensive operation at the nursery including the activities of: mowing and plowing in the cover crop, fumigation of the soil with methyl bromide, fertilization with N, P, and K, and bed shaping. All of these activities are conducted with the use of a diesel powered tractor. Following these activities, seed sowing and mulching are carried out with a vacuum sower and modified manure spreader, respectively, pulled by a diesel tractor. Management of the seed beds once planted include the activities of irrigation, a second fertilization of N, P, and K, application of the herbicides Goal®, Fusilade®, and Cobra®, insecticides Asana® and chlorpyrifos, and fungicide Quilt®, and tip, lateral, and root pruning of the seedlings. Finally seedlings are harvested and stored in the cooler for 48 hours prior to transportation to the plantation site.

Transportation of Seedlings to Plantation Site (TR – II)

The seedlings are transported in a diesel fueled semi-box trailer from the nursery to the plantation site.

Plantation Management and Harvesting

Prior to the seedlings arriving at the plantation area, the site must be prepared for planting. This includes chopping, piling, and burning of residues from the previous harvest, followed by disking and bedding of the soil. These activities are powered by diesel fueled tractor. Once beds are formed, the seeds are planted by use of tractor and mechanical planter. Silvicultural operations at the plantation include fertilization with N, P, and K, application of the herbicides Arsenal® and Oust®, and insecticide Mimic® and a controlled burn. Fertilization is assumed to occur at year 5, herbicide and insecticide applications between year 6 and year 10, and a burning in year 14 in order to make the stand more accessible for thinning operations in year 15. Also prior to thinning, the stand may be cruised in order to assess which trees to remove. Energy and emissions data for this activity were not considered for the purposes of this analysis because, although it is an important activity for forest management, the total energy and material use required represent an insignificant proportion (<1%) of the system total. Thinning activities include cutting of targeted trees, dragging to the loading area, removing branches, and chipping into the trailer for delivery to the mill. Each of these activities requires a specific piece of machinery, respectively: a feller-buncher, a skidder, a de-limber, a loader, and a chipper. It is assumed that only pulpwood size trees and residues, biomass too small for conventional pulpwood and other timber products, from the thinning and final harvest activities are used for biofuel production. However, there are also chip and saw and sawtimber size trees harvested at both the time of thinning and harvesting. Therefore, the total energy and material consumption at the plantation is allocated proportionately by considering the proportion of total biomass produced intended for biofuel production. Final harvest is assumed to occur at year 25 with the same operations conducted and equipments used at the time of thinning.

Transportation of Wood Chips to Ethanol Mill (TR – III)

The wood chips are transported in a diesel fueled semi-box trailer from the plantation to the ethanol mill.

Ethanol Production

The ethanol production process is divided into six primary operation areas including: feedstock storage and handling, pretreatment, simultaneous saccharification and co-fermentation (SSCF), product and water recovery, waste water treatment, and steam and electricity production. This process design is based on the most recent experimental results achieved by the National Renewable Energy Laboratory (Aden *et al.* 2002).

Feedstock storage and handling. Green wood chips (50% moisture) are delivered to the mill in semi-truck trailers and piled in the storage area where they are manipulated by bulldozers. Chips are then passed under a magnetic separator and washed to remove contaminants and impurities. The resulting solution is sent to the wastewater treatment area of the plant. The washed chips are then screened by size and distributed to the waste disposal, size reduction, or pretreatment areas depending upon the size of the material. Those materials deemed too large or otherwise unusable are sent to waste disposal, while those sent to size reduction are sent afterwards to pretreatment.

Pretreatment. In the pretreatment process considered, the washed and screened wood chips are steamed at low pressure at 100°C to remove non-condensables and increase the efficiency of hydrolysis. Following steaming, dilute sulfuric acid (1.1%) is added to the reactor and temperature and pressure are increased to 190°C and 12.1 atm, respectively. Following this process, the resultant hydrolyzate liquid and remaining solids are flash cooled, and the solids washed and pressed to separate the liquid and solid fractions. The liquid fraction is then conditioned through over liming in order to neutralize the solution and precipitate gypsum, which is filtered out as a co-product. The remaining hydrolyzate is mixed back with the solids and dilution water and sent to the SSCF area.

Simultaneous saccharification and co-fermentation (SSCF). In this area, the remaining cellulose is saccharified into glucose with the use of cellulase enzymes, which consist of endoglucanases, exoglucanases, and beta-glucosidases all produced from the bacteria *Trichoderma reesei*. These enzymes are purchased from a manufacturer and stored on site. The resulting glucose and other sugars hydrolyzed in the pretreatment area are fermented to ethanol by the recombinant bacteria *Zymomonas mobilis*, which is grown in a seed fermentation vessel. Saccharified slurry, nutrients, and seed inoculum are combined and processed through a series of fermentation tanks, where the enzymes continue to break down the cellulose while the sugars are fermented simultaneously. The resulting ethanol broth is stored in a beer well before being sent to the distillation area.

Product and water recovery. The ethanol beer is distilled in two columns, the first of which removes the dissolved CO_2 and most of the water, while the second concentrates the ethanol to an azeotropic composition. The water from this azeotropic mixture is then removed by vapor phase molecular sieve adsorption. The vents are scrubbed and 99% of the ethanol is recovered. Finally, a 99.5% pure ethanol vapor is condensed and pumped to storage. The syrup at the bottom of the distillation columns is fed to the boiler along with the remaining solids from the previous processes. The water that does not evaporate is either reused as recycled cooling water or sent to waste water treatment.

Waste water treatment. All plant wastewater is initially screened to remove large particles, which are collected and sent to waste disposal. Screening is followed by anaerobic digestion and then aerobic digestion to digest organic matter in the stream. Anaerobic digestion produces a biogas stream with a high concentration of methane that is fed to the combustor. Aerobic digestion produces a clean water stream for reuse in the process as well as a sludge that is also burned in the combustor.

Combustor, boiler and turbo-generator. All of the lignin along with the fractions of cellulose and hemicelluloses that are not converted, the syrup produced from the distillation, waste water treatment sludge, and biogas stream from the anaerobic digestion are all combusted to produce steam and electricity to power the plant operations.

Transportation of Ethanol to Final Pumping Station (TR – IV)

The ethanol is transported in a diesel fueled semi-tanker from the ethanol mill to the pumping station.

Material Inputs

Material inputs consist of chemicals, equipment, fuels, and water. These are allocated in each LCI stage based on the output required per functional unit for the particular stage under consideration. For instance, the amount of fertilizer used in the seed orchard that is considered as an input is determined by calculating the product of the fertilization rate (kg/acre) and the number of acres required to produce the amount of seed needed per functional unit. Similarly, inputs of component materials in equipment are determined by calculating the product of the weight (kg) of the component and the time (hr) of use divided by the lifetime (hr) of the equipment. Fuel use is calculated based on the usage rates per machine. The total water use calculated includes mixture with liquid applications of pesticides, insecticides, and herbicides, irrigation, and use in the ethanol production stage.

Table 3-2 gives the required outputs and area or distance necessary (depending on stage) for each LCI stage to produce and deliver one functional unit, 1000 liter of ethanol.

Seed Orchard Management and Seed Processing

The number of acres required in the seed orchard was determined based on the slash pine specific values of 100 seeds per cone and 97.50 cones per tree, and a seed orchard tree density of

48 trees per acre. Also, a seed mortality rate of 20% was assumed. A total of 118.66 seeds were found to be necessary, requiring 2.54E-4 acres.

Chemicals. The chemical inputs of the seed orchard stage include N (ammonium nitrate), P (diammonium phosphate), and K (potassium chloride) fertilizers, Goal® (24 % oxyfluorfen) and Fusilade® (24.5% fluazifop-p-butyl) herbicides, and Asana® (8.4% esfenvalerate) and chlorpyrifos (42%) pesticides. The fertilizers are applied at a rate of 20.41, 9.07, and 6.80 kg/acre, respectively, for N, P, and K. When multiplied with the required number of acres, the amount used is found to be 5.18E-3, 2.30E-3, and 1.73E-3 kg, respectively. Goal® and Fusilade® are applied at rates of 0.18 and 0.30 liters/acre, respectively. The total amount used was found to be 4.50E-5 and 7.50E-5 liters, respectively. Asana® and chlorpyrifos are applied at rates of 0.30 and 0.24 liters/acre, respectively, and the total amount used was found to be 7.50E-5 and 6.00E-5 liters.

Equipment. The inputs of equipment considered in the seed orchard and processing facility include the tractor and attachments, tree shaker, drying equipment, de-winger, cleaner, size sorter, and weight sorter. A particular composition was assumed for each piece of equipment. The component materials include carbon steel, aluminum, copper, zinc, plastics, and rubber. The composition for each is given in Table 3-3. Allocation was performed by using equation 3-2 above. By summing the materials used in each piece of equipment, the total use was found to be 3.28E-3, 2.63E-5, 9.87E-6, and 3.29E-6, and 4.01E-4, 4.07E-4 kg for carbon steel, aluminum, copper, zinc, plastics, and rubber, respectively.

Fuels. The fuels used in the seed orchard stage include diesel, propane, and electricity. Diesel is used to fuel the tractor and tree shaker, which consume the fuel at the rate of 15.14 liters/hour. Through solving equation 3 – 3 above, the total amount of diesel used with the tractor and tree shaker was found to be 0.014 liters. Propane is used in the seed drying process at the rate of 1.89 liters/bushel of seeds. For slash pine, there is an average of 12,000 seeds per bushel. Thus, the total propane used for the seed processing was found to be 0.075 liters. Electricity powers all equipment during the seed processing phase. Each machine is assumed to use electricity at a rate of 0.61 MJ/hour and based on the total time of use for each machine, the total electricity consumed at the seed processing facility was found to be 0.099 MJ.

Water. Water use at the seed orchard stage includes only the water required to dilute the herbicide and pesticides to the appropriate levels. The total water use was found to be 0.115 liters.

Transportation of Seeds to Nursery (TR – I)

During the transportation step, the only material inputs are the components of the transport vehicle and the fuel consumed during the transportation.

Equipment. The use of carbon steel, aluminum, copper, zinc, plastics, and rubber was calculated by multiplying the fraction of the weight the substance's weight found to be 18.31, 2.09, 0.78, 0.26, 2.09, and 2.61 kg, respectively.

Fuels. Total diesel use was found based on an average fuel economy of 1.91 liters/km, a roundtrip distance of 321.87 km, and a 5.17E-5 proportion of the load allocated per functional unit to be 3.19E-4 liters.

Nursery Management

The number of acres required at the nursery was calculated based on a seedling density of 28 seedlings per square foot in the seed beds and 12 beds per acre. A seedling mortality rate of 15% was assumed. The number of seedlings and requisite acres in the nursery were determined to be 98.89 and 1.23E-4, respectively.

Chemicals. Inputs of chemicals at the nursery include N (ammonium nitrate), P (diammonium phosphate), and K (potassium chloride) fertilizers, Goal® (24 % oxyfluorfen), Fusilade® (24.5% fluazifop-p-butyl), and Cobra® (23.2% lactofen) herbicides, Asana® (8.4% esfenvalerate), chlorpyrifos (42%), and thiram (75%) pesticides, Bayleton® (50% triadimefon) and Quilt® (18.7% azoxystrobin, propiconazole) fungicides, and methyl bromide fumigant. N, P, and K are applied twice each at rates of 27.27, 20.45, and 16.36 kg/acre, respectively. Based on the acres required, total use for N, P, and K was found to be 6.69E-3, 5.02E-3, and 4.01E-3 kg, respectively. Goal®, Fusilade®, and Cobra® are applied 8, 1, and 3 times at rates of 1.42, 0.71, and 0.53 liters/acre, respectively. The total use of these herbicides was found to be 1.39E-3, 8.70E-5, and 1.96E-4, respectively. Asana®, chlorpyrifos, and thiram are applied 10, 2, and 1 times at rates of 1.63, 0.95, and 7.89E-7 liters/acre, respectively. Total use of these pesticides was found to be 1.99E-3, 2.32E-4, and 7.80E-5, respectively. Bayleton® and Quilt® were used 1 and 3 times at rates of 9.86E-8 and 0.89 liters/acre, respectively. Total use was found to be 9.75E-6 and 3.26E-4, respectively. The fumigant methyl bromide is applied once at 181.82 kg/acre and total use was found to be 2.23E-2.

Equipment. The inputs of equipment considered at the nursery include two different size tractors (Ford 3910 and 7610) with attachments and irrigation equipment. By summing the quantity of materials used in each piece of equipment, the total use was found to be 5.29E-4, 6.73E-4, 2.27E-5, 7.55E-6, 6.04E-5, and 7.55E-5 kg for carbon steel, aluminum, copper, zinc, plastics, and rubber, respectively.

Fuels. The fuels used in the nursery include diesel and electricity. Diesel is used to fuel the tractors, which consume fuel at the rate of 15.14 and 30.28 liters/hour for the smaller and larger tractor, respectively. Through solving equation 3 – 3 above, the total amount of diesel used was found to be 0.045 liters. Electricity supplies power to the cooler where arriving seeds and seedlings ready for departure are stored. The cooler is assumed to use electricity at a rate of 41.67 MJ/hour and based on the total storage time, the total electricity consumed at the nursery was found to be 9.884 MJ.

Water. The water used at the nursery is for stratification, irrigation, and mixing with applications of agrichemicals. Water for stratification purposes is assumed to be used at a rate of 3.34 liters/kg of seed. Irrigation is conducted over the eight month growing cycle at varying rates. A total of 834.62 liters are used during this period per functional unit. Water is mixed with agrichemicals at a rate of 113.7 liters/acre. Total water use was determined to be 835.01 liters.

Transportation of Seedlings to Plantation Site (TR – II)

Equipment. The use of carbon steel, aluminum, copper, zinc, plastics, and rubber was found to be 9.15, 1.05, 0.39, 0.13, 1.05, and 1.31 kg, respectively.

Fuels. Total diesel use was found based on an average fuel economy of 1.91 liters/km, a roundtrip distance of 160.93 km, and a 1.38E-4 proportion of the load allocated per functional unit to be 0.04 liters.

Plantation Management and Harvesting

The number of acres required at the plantation site was determined based on a yield of 40 and 100 green short tons per acre at the time of thinning and harvesting, respectively. A total of 0.112 acres were found to be necessary to produce the 5.814 green tons of biomass required.

Chemicals. The chemical inputs of the plantation stage include N (ammonium nitrate), P (diammonium phosphate), and K (potassium chloride) fertilizers, Arsenal® (28.7% imazapyr, isopropylamine salt) and Oust® (71.25% sulfometuron methyl, metsulfuron methyl) herbicides, and Mimic® (70% tebufenozide) pesticide. The fertilizers are applied at a rate of 149.00, 51.82, and 49.00 kg/acre, respectively, for N, P, and K. When multiplied with the required number of acres, the amount used is found to be 8.34, 2.90, and 2.74 kg, respectively. Arsenal® and Oust® are applied at rates of 0.11 and 0.05 liters/acre, respectively. The total amount used was found to be 6.16E-3 and 2.80E-3 liters, respectively. Mimic® is applied twice at a rate of 0.24 liters/acre and the total amount used was found to be 2.65E-2 liters.

Equipment. The inputs of equipment considered at the plantation include the tractor and attachments, feller-buncher, skidder, de-limber, loader, and chipper. By summing the materials used in each piece of equipment, the total use was found to be 1.27, 0.15, 0.05, 0.02, 0.15, and 0.18 kg for carbon steel, aluminum, copper, zinc, plastics, and rubber, respectively.

Fuels. The fuels used in the plantation stage include diesel and gasoline. Diesel is used to fuel all equipment, while gasoline is used for the controlled burn. The total amount of diesel used was found to be 31.62 liters. The total amount of gasoline used was found to be 0.03 liters.

Water. Water use at the plantation includes only the water required to dilute the herb- and pesticides to the appropriate levels. The total water use was found to be 25.47 liters.

Transportation of Wood Chips to Ethanol Mill (TR – III)

Equipment. The use of carbon steel, aluminum, copper, zinc, plastics, and rubber was found to be 9.15, 1.05, 0.39, 0.13, 1.05, and 1.31 kg, respectively.

Fuels. Total diesel use was found based on an average fuel economy of 1.91 liters/km, a roundtrip distance of 160.93 km, and a 0.23 proportion of the load allocated per functional unit to be 71.60 liters.

Ethanol Production

Chemicals. Chemicals at the ethanol mill include clarifier polymer, sulfuric acid, calcium carbonate, diammonium phosphate, wastewater chemicals, wastewater polymer, boiler chemicals, and cooling tower chemicals. These were used in quantities of 0.90, 105.11, 76.56, 5.21, 1.85, 0.01, 0.03, and 0.06 kg, respectively. These values are based on the process design described by Aden *et al*. (2002).

Equipment. Values for equipment materials are based on Hill *et al*. (2006). Materials are lumped into the categories of carbon steel, stainless steel, and concrete and the total amounts per functional unit are 0.328, 0.208, and 5.00 kg, respectively.

Fuels. Propane and electricity are the two fuel sources at the ethanol mill. Propane is used at the stage of feedstock storage and handling for maneuvering the incoming loads of biomass. Total use was calculated to be 16.34 liters. Electricity is consumed in each stage of the conversion process for powering equipment and other uses. It is assumed that 3.225 MJ of electricity are used per kg of biomass converted. Also, 0.002 MJ of electricity are used per liter of wastewater for treatment purposes. This amounts to a total of 17,009 MJ of electricity consumption. However, the lignin separated out from the biomass during the hydrolysis stages is capable of producing 18,986 MJ. Thus, there is a net output of electricity from the ethanol mill of 1,977 MJ.

Water. Total water consumption at the ethanol mill per functional unit was determined to be 1,375 liters for washing biomass feedstock and providing solution for the processes of bacteria production.

Transportation of Ethanol to Final Pumping Station (TR – IV)

Equipment. The use of carbon steel, aluminum, copper, zinc, plastics, and rubber was found to be 18.31, 2.09, 0.78, 0.26, 2.09, and 2.61 kg, respectively.

Fuels. Total diesel use was found based on an average fuel economy of 1.91 liters/km, a roundtrip distance of 321.87 km, and a 0.03 proportion of the load allocated per functional unit to be 20.33 liters.

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BIOGRAPHICAL SKETCH

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