LIFE CYCLE AND COST BENEFIT ANALYSES OF ETHANOL PRODUCTION FROM SLASH PINE (*PINUS ELLIOTTII*) PLANTATIONS

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Abstract

This paper considers potential cellulosic ethanol production from Southern slash pine (*Pinus elliottii*) plantations. The net energy balance (NEB), emissions and associated environmental impacts, unit cost of ethanol production, and associated changes to forest land values are calculated and preliminary results are given. The NEB is found to be positive at 2.2, meaning that for every unit of energy input to the system, 2.2 units of energy are obtained through the ethanol produced. Associated impacts are significant, but less so than the corn starch to ethanol production process. The unit cost of ethanol produced in the manner considered, a two stage dilute sulfuric acid hydrolysis, was found to be $0.44 per liter, greater than the current cost of production of ethanol from corn. The forestland values, demonstrated to increase under various degrees of ethanol production, were found to be negative under the maximum ethanol production scenario.

**Keywords:** Bioenergy, net energy balance, non-industrial private forests, two stage dilute sulfuric acid hydrolysis, unit cost

Introduction

By the year 2020, the total world energy consumption is projected to grow by 77% over 1990 levels, from 347.3 quadrillion BTUs in 1990 to 613.0 quadrillion BTUs in 2020 (EIA 2006). Over 85% of our energy supply comes from fossil fuel based energy resources like oil, coal, and natural gas (EIA 2006). The use of these fuels is linked to a host of environmental, economic, and political concerns. As outlined in the most recent report of the Intergovernmental Panel on Climate Change (IPCC), the occurrence of global climate change is considered to be driven by
human influence through the release of carbon dioxide and other greenhouse gases (GHGs) into the atmosphere through the combustion of fossil fuels (IPCC 2007). The subsequent need for novel energy sources which can substitute for transport fuels like gasoline and diesel has driven much research in the area of renewable agriculture and forest based biofuels such as ethanol. Energy consumption by the transportation sector in the U.S. accounted for about 28.4% of total energy consumption in the country in 2006 (EIA 2006). In order to be a viable energy source and displace such fossil based transport fuels such as gasoline and diesel, biofuels must provide a significantly high energy yield and should be economically competitive with current fossil based alternatives.

Biomass currently represents nearly half of the renewable energy production in the United States, producing about 3% of the nation’s total energy supply (EIA 2006). The potential for biomass to develop into a major energy source has been documented recently by the United States Department of Agriculture, which estimated that enough biomass is grown annually in the country to offset one third of current demand for transport fuels without interrupting food, feed, and export supplies (Perlack et al. 2005). Several studies have been conducted analyzing the environmental and economic impacts of utilizing various biomass sources for bioenergy production. Most of these suggest that, if managed properly, biomass sources hold the potential to meet a significant portion of our energy supply while achieving meaningful reductions in greenhouse gases (GHGs) and other pollutants as well as enhancing rural economies (Hill et al. 2006, Childs and Bradley 2008).

Based on this rationale, several government initiatives have been passed at the state, federal, and international levels encouraging the production of biofuels from various agricultural and forestry feedstocks. At the national level, President Bush 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). Although the policies discussed above 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 corn starch. This scenario has led to concern over increasing corn prices and the so-called “food vs. fuel” debate. Additionally, the energy ratio of corn starch based ethanol has been questioned, being reported as 0.71 by Pimentel and Patzek (2005) 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, peatlands, tropical forests, and other intact ecosystems to grow energy feedstocks far outweighs the GHG offsets of burning biofuels rather than fossil fuels (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 21 billion gallons of cellulosic ethanol 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, also known as marginal, lands, crop residues, and woody biomass. This feedstock flexibility represents an opportunity to utilize lower valued 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.
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 (Weir and Greis 2002). In Florida, slash pine (Pinus elliottii) is the dominant forest species, covering approximately 5.1 million acres, or 34% of the total forestland in the state (Carter and Jokela 2002). Due to the diminished returns from thinnings and other small diameter wood, there can be less incentive for landowners to conduct this management practice. This leads to a situation in which forests can 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). 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.

This study addresses the potential of forest based biomass as a feedstock for ethanol production based on the net energy balance (NEB), total system emissions and associated environmental impacts, unit cost of ethanol production, and associated valuation of forestlands in the face of a biofuels market. Data for the analysis is based on current practices of nonindustrial private forest (NIPF) owners in the U.S. South and the two-stage dilute sulfuric acid conversion process of wood chips to ethanol. Results for the analyses are preliminary.

Methods

Life Cycle Analysis: Net Energy Balance

The ethanol production process was divided into the ten steps of: 1) Seed Orchard Management, 2) Transportation of seeds to Nursery, 3) Nursery management, 4) Transportation of seedlings to the plantation site, 5) Site preparation before planting, 6) Planting and plantation management (including thinning), 7) Harvesting, 8) Transportation of wood chips to ethanol mill, 9) Ethanol production at ethanol mill, and 10) Transportation of ethanol to gas station (Figure 1).

The total energy inputs in the form of diesel, gasoline, machinery and plant construction, propane, electricity, and chemicals required to produce one functional unit of ethanol at 10 identified steps were summed up to calculate total energy inputs of the system. The calorific value of ethanol (21.13 MJ/l) was multiplied with the total quantity of ethanol produced (1000 L) to calculate the total energy output of the system. Using the formula, \[ \text{NEB} = \frac{\text{Output Energy}}{\text{Input Energy}} \], the required ratio was calculated for the system.

In the seed orchard stage, the processes considered were: collection of cones from the seed orchard, drying of cones in a two stage process, seed preparation through the various processes of de-winging, cleaning, size sorting, and weight sorting, and storage for 7 days in a cooler before they are transported to the nursery. At the nursery, the seeds are stored in a cooler for about 240 hours, then the stratification starts for which water use for the required number of seeds was calculated. Then seeds are kept in a cooler once again for 14 days, after which seeds are treated with fungicide and bird repellant, and finally the seeds are stored once more in a
cooler for 10 days before planting. The activities of site preparation, identified by interviewing stakeholders, were chopping, piling, burning, disking, bedding, and herbicide application. It was found that herbicide was used once to remove weeds before planting seedlings. The operations included in planting and plantation management are: seedling planting, fertilizer application, insecticide application, herbicide, prescribed burning and thinning.

Using a CRIFF model, the biomass availability at the time of thinning was found to be about 19 tons per acre. Assuming that only pulpwood and harvesting residues obtained at the time of thinning will be utilized for ethanol production, their available quantities on a dry mass basis per acre of land was calculated. Based on the total availability of dry biomass at the time of thinning, the total acreage required to produce sufficient quantities of wood chips for ethanol production was found. Total consumption of diesel and gasoline was calculated based on the total acreage required, fuel consumption, and machine use rates. It was assumed that wood available from the different forest products will be chipped on the site of harvesting/thinning once the required moisture content is achieved.

The technology used for converting slash pine wood chips into ethanol was a two stage dilute sulfuric process. The inputs and outputs associated with the production of ethanol from sugarcane bagasse are given by Kadam (2000). These ratios were used and were adjusted for slash pine to calculate quantities of total inputs and outputs. As the quantities of sugar that can be hydrolyzed to produce ethanol are different for different cellulosic feedstocks, the ethanol yield was found to be 236.7 l/dry ton of slash pine biomass at 15% moisture content for slash pine biomass. Lignin is produced during the conversion process of wood chips into ethanol. Lignin has a high calorific value (19.22 MJ/kg) and can be used in boilers for producing heat. The total electricity consumption required during the conversion process was subtracted from the total

**Figure 1. System boundary for life cycle analysis**
potential of electricity to calculate net electricity consumption of the ethanol mill. The total life time of an ethanol mill was considered to be 15 years (Solomon et al, 2007) and the capacity of a mill was taken to be 50 million gallons/year.

The total distance traveled by a tanker for making a round trip was taken as 300 miles or 480 km (i.e. 240 km for each direction). An assumption has been made that 70% of the gross weight of all machines is made up of steel. Average use rates and the fuel consumption rates for all the machines have been recorded after discussions with stakeholders. The total weight of the steel was allocated to the one functional unit. After allocating the exact steel used for every machine used in a step, the sum of the allocated steel was found for a particular step by summing allocated steel for each individual machine.

Life Cycle Analysis: Emissions and Environmental Impacts

Assuming that all the energy required for producing different materials will be in the form of electricity, the net emissions of the system due to energy and material use have been determined separately. The total electricity used was assumed to be supplied by the national grid. The production mix of the national grid, about 49%, 2%, 20% and 2.5% of the total electricity in U.S., is produced using coal, petroleum, natural gas and other renewable resources, respectively. The total energy consumed due to use of diesel and gasoline at every step was multiplied by the emissions factors. Similarly, total electricity consumption for every step was identified and was then multiplied by the emissions factors, with due adjustment to electricity mix of the nation. In this way, the total quantities of different pollutants generated due to energy use in the system were quantified.

Emissions of pollutants due to material use were also quantified. For fertilizer use, it was assumed that 5% of the total quantities of nitrogen, phosphorus and potassium fertilizers used in the system will end up as nitrate, phosphates and potash ions, causing water pollution. Similarly, fumigants, fungicides, herbicides and insecticides were also considered to be sources of pollutants. Biogas methane and carbon dioxide produced at the ethanol mill were also considered for quantifying emissions. Finally, emissions generated due to burning of lignin were included in the analysis. In this way, the total quantities of different pollutants generated due to material use in the system were quantified. Finally, both types of emissions were added to quantify the total quantities of different pollutants generated in the system. Based on the aggregated values of different pollutants, different environmental impacts of global warming, eco-toxicity, acidification and eutrophication, the impact factors of different pollutants as given by TRACI (Tool for the Reduction and Assessment of Chemical and other environmental Impacts) database were used (Bare et al., 2003).

Cost Benefit Analysis: Unit Cost Analysis

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. 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 1000 L of ethanol produced are given in Table 1.

### Table 1. Material and energy inputs and outputs per 1000 L of ethanol produced

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Quantity</th>
<th>Units</th>
<th>Cost ($/unit)</th>
<th>Outputs</th>
<th>Quantity</th>
<th>Units</th>
<th>Cost ($/unit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biomass</td>
<td>4.66</td>
<td>Ton</td>
<td>33.87</td>
<td>Ethanol</td>
<td>1000.00</td>
<td>L</td>
<td>varies</td>
</tr>
<tr>
<td>Hydrated lime</td>
<td>54.92</td>
<td>Kg</td>
<td>0.08</td>
<td>Gypsum</td>
<td>131.50</td>
<td>kg</td>
<td>0.03</td>
</tr>
<tr>
<td>Water</td>
<td>15171.36</td>
<td>L</td>
<td>0.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NH₃</td>
<td>105.62</td>
<td>kg</td>
<td>0.37</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diesel</td>
<td>5.25</td>
<td>gal</td>
<td>2.88</td>
<td>NPV =</td>
<td>0.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H₂SO₄</td>
<td>202.79</td>
<td>kg</td>
<td>0.03</td>
<td>Rate =</td>
<td>0.10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electricity</td>
<td>1468.60</td>
<td>MJ</td>
<td>0.03</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ash disposal</td>
<td>326.63</td>
<td>kg</td>
<td>0.02</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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 at $5.00 per green ton. The total delivered cost based on these base case values was therefore determined to be $33.82 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:

\[
\text{NPV} = \sum_{t=1}^{15} [(B_t \times e^{-rt}) \ - \ (C_t \times e^{-rt})]
\]

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). 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.

**Cost Benefit Analysis: Forestland Valuation**

Forest biomass calculations for above and below ground biomass were calculated. From these calculations the income to the forest owner was calculated based on the revenues from timber harvest and sale of biomass for ethanol production. Forest stand data were simulated using the growth and yield simulation program GaPPS 4.20. The total outside bark green weight was
divided into the 4 product classes of residues, pulpwood, chip and saw, and sawtimber based on small end diameter (0.1”, 2.0”, 6.0”, 8.0”), minimum length (0.1’, 5.0’, 8.0’, 8.0’), and length increment (0.1’, 1.0’, 4.0’, 8.0’), respectively.

Total costs (see Table 2) were based on Smidt et al. (2005), Andrew’s Nursery, and personal communication with Natural Resource Planning Services, Inc. Costs were discounted to present values (PV) using the continuously discounted formula of:

\[ FV = FV \times e^{-r\times t} \]

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. Values were then accumulated to arrive at a cumulative present value of costs every year from year 0 to 30.

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

<table>
<thead>
<tr>
<th></th>
<th>No.</th>
<th>Price</th>
<th>Cost</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site prep</td>
<td>1</td>
<td>$323.00</td>
<td>$323.00</td>
<td>0</td>
</tr>
<tr>
<td>chopping/shearing</td>
<td>1</td>
<td>$50.00</td>
<td>$50.00</td>
<td>0</td>
</tr>
<tr>
<td>piling</td>
<td>1</td>
<td>$48.00</td>
<td>$48.00</td>
<td>0</td>
</tr>
<tr>
<td>burning piles</td>
<td>1</td>
<td>$60.00</td>
<td>$60.00</td>
<td>0</td>
</tr>
<tr>
<td>bedding</td>
<td>1</td>
<td>$105.00</td>
<td>$105.00</td>
<td>0</td>
</tr>
<tr>
<td>herbicides</td>
<td>1</td>
<td>$60.00</td>
<td>$60.00</td>
<td>0</td>
</tr>
<tr>
<td>seedlings</td>
<td>720</td>
<td>$0.06</td>
<td>$41.76</td>
<td>0</td>
</tr>
<tr>
<td>planting</td>
<td>1</td>
<td>$45.00</td>
<td>$45.00</td>
<td>0</td>
</tr>
<tr>
<td>fertilizer</td>
<td>1</td>
<td>$49.23</td>
<td>$49.23</td>
<td>5</td>
</tr>
<tr>
<td>herbicide</td>
<td>1</td>
<td>$62.04</td>
<td>$62.04</td>
<td>6</td>
</tr>
<tr>
<td>burning</td>
<td>1</td>
<td>$30.00</td>
<td>$30.00</td>
<td>11</td>
</tr>
<tr>
<td>tax rate (per year)</td>
<td>1</td>
<td>$7.00</td>
<td>$7.00</td>
<td>All</td>
</tr>
</tbody>
</table>

The value of the timber benefits to the land owner was determined using current South-wide averages for stumpage values per ton of pulpwood ($8.11), chip and saw ($18.88), and sawtimber ($36.59) obtained from Timber Mart-South (2008). The growth and yield data provided by GaPPS was divided into the four size classes shown in Table 1 for each year of the plantation from year 5 to year 30. The value of harvesting the stand for purely timber benefits was calculated in each year from year 5 to year 30 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 costs associated with site preparation and silvicultural treatments to obtain the cumulative NPV of the stand in every year from zero to 30.

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: 1) no biofuel feedstock, 2) harvest residues only, 3) one quarter of pulpwood plus residues, 4) one half of pulpwood plus residues, 5) all pulpwood plus residues, and 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. The NPV in each year was then used to calculate the land expectation value (LEV), which returns the value of the stand under consideration assuming perpetual rotations. LEV was found by solving the following formula:

\[ \text{LEV} = \frac{\text{NPV}}{1 - e^{-rt}} \]

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.

**Preliminary Results**

**Life Cycle Analysis: Net Energy Balance**

The net energy ratio was found to be 2.2 implying that for every joule of energy spent in producing ethanol, there is a net gain of 2.2 joules of energy. This is a higher net energy ratio than that achieved from ethanol production from corn grain (energy ratio of corn is 1.67) as reported by Shapouri and McAloon (2005). The total biomass required to produce one functional unit of ethanol was found to be 4224.83 kg. The distribution of total consumption of energy in the form of electricity, diesel, gasoline and propane for the whole system was analyzed and results are shown in Figure 2.

As observed from Figure 3, maximum electricity consumption occurs at ethanol production (Production) followed by the planting stage (Planting). Energy use due to diesel consumption was found to be highest for the transportation step TR-II followed by the Production step. The total energy due to gasoline and propane consumption was found to be approximately 1 and 1.5 MJ, respectively (gasoline is used only in the Planting and Site-prep steps while propane is used only in the Orchard step). This signifies that maximum energy is used at the Production step and least in the TR-IV step. When the obtained NEB was compared with other energy crops, the NEB from slash pine was quite impressive. For example, ethanol produced from corn and corn stover has an NEB of approximately 1.1 and 1.7, respectively (Lavigne and Powers 2007), which is significantly lower than the NEB of ethanol derived from slash pine.

**Life Cycle Analysis: Emissions and Environmental Impacts**

The total amount of carbon dioxide generated during the whole process was about 5970 kg, and nearly all (97.5%) was generated at the Production step. Total quantity of biomass required was about 4,225 kg and assuming that the biomass has 50% carbon, the total carbon sequestered in the above ground biomass was found to be 2112.4 kg. The total carbon present in produced carbon dioxide was about 163 kg. This implies that net carbon sequestered in the system is positive.
Figure 2. Energy use at different steps of the system.

Figure 3. Ethanol unit production cost breakdown.
The quantities of pollutants generated due to energy and material use were multiplied with the impact factors, given in TRACI database, for quantifying selected environmental impact. The maximum global warming is caused due to production of greenhouse gases like carbon dioxide and methane during the Production step. Similarly, maximum acidification potential was also found associated with the same step. This was primarily due to the use of lignin for heat production and importing of electricity from the grid. Similarly, the maximum contribution for eutrophication and eco-toxicity was found associated with the Planting step. This was due to the use of fertilizers and other chemicals.

Cost Benefit Analysis: Unit Cost Analysis

The unit cost of ethanol was calculated to be $0.44 per liter or $1.67 per gallon using the mean delivered feedstock cost of $33.87 per 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 $0.65 per liter and $2.47 per gallon, respectively. The largest single contribution to this cost is the cost of the biomass feedstock, which represents 37% of the unit cost of ethanol production. Plant construction, electricity use, and ammonia represent the next three largest contributors at 31%, 11%, and 9%, respectively (Figure 3). 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.

Cost Benefit Analysis: Forestland Valuation

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 highest LEV obtained from the biofuel feedstock production scenario of harvest residues (scenario 2), peaking in year 23 of the rotation at $298.20 per acre. The lowest yielding scenario was the maximum biomass production scenario, reflecting the higher values for wood products than for biofuel production. The highest yielding scenario 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).

Discussion

The preliminary results of these analyses further indicated that the potential of Southern NIPF lands as a source of feedstock for cellulosic ethanol. With an NEB higher than that of corn starch based ethanol, which currently provides the majority of the ethanol produced in the U.S., the use of forest based thinnings and harvest residues may be an attractive option for bioenergy production. Although the environmental impacts are significant, they remain favorable in comparison to those of corn based ethanol. Though energetically and environmentally advantageous, the economic criterions of ethanol produced from woody biomass grown on Southern NIPF lands are only partially fulfilled. The unit cost of this ethanol is greater than that of corn based ethanol, rendering it a less viable alternative from a financial viewpoint. There is,
however, an increase in the modeled land value to the NIPF owner, which may lend to societal welfare by allowing these lands to remain in forest management, preserving their associated environmental services, and enhancing the rural sector of the economy.

Further research to enhance these analyses would include exploring other commercial forestry species for ethanol production and examining alternative conversion technologies. Furthermore, alternative biomass production scenarios and/or cropping systems might lend more insight into optimal solutions. One primary concern that must also be addressed is how to appropriately develop the forest and agricultural bioenergy sectors without impacting existing product sectors, such as the food, feed, and fiber markets.

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