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Abstract

The goal of this study is to develop a feedstock supply chain for a potential commercial-scale biorefinery in Tennessee that optimizes both economic cost and GHG emissions. Since some factors such as land conversion and harvest/storage system have an effect on both the economic cost and GHG emissions, a trade-off might exist between these two objectives if one factor has a positive impact on cost [GHG emissions] while a negative influence on GHG emissions [cost]. Our findings suggest that the cost of biofuel feedstock supply system is sensitive to the land that goes into the production of the feedstocks required by the bioenergy industry. Also, considering additional criteria of environmental performance will result in increased feedstock costs, which may dampen the industry’s willingness to incorporate the environmental criteria in the decision of biorefinery location. However, the Pareto curve derived from this study implies that the GHG emissions from land use for feedstock production can be reduced considerably through reasonable incentives from the government to the biofuel industry. This information is important since it can help both the government and investors develop a more balanced and sustainable bioenergy sector in the state and the southeastern region.

Keywords: GHG emissions, cost, switchgrass, Pareto optimal, GIS

1. Introduction

Producing biofuels from lignocellulosic biomass (LCB) has been suggested as a way to mitigate the dependence on fossil fuels and the production of greenhouse gas (GHG) emissions in the United States. The Renewable Fuel Standard (RFS2) in the Energy Independence and Security Act (EISA) of 2007 has mandated 16 billion gallons of LCB-based biofuels per year for transportation use by 2022 (U.S. Congress, 2007). It is anticipated that considerable amounts of LCB feedstock will be needed to fulfill this goal. Thus, the configuration of the feedstock supply chain for biofuels should be carefully examined since the quality and quantity of feedstock will influence the cost of biofuels production. GHG emissions

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associated with LCB feedstock supply from changes in land use and LCB feedstock production, storage, and transportation activities can also impact the sustainability of LCB-based biofuel production.

Switchgrass, a perennial grass native to North America, has a high potential for biofuel production. It has high yields and a lower demand for fertilizer and chemicals than row crops (Wright, 2007). With abundant sunshine and precipitation, the southeastern states of the U.S. such as Tennessee have comparative advantages for switchgrass production. The Tennessee Biofuel Initiative program was established in 2007 to develop a switchgrass-based biofuels sector in the state (Tiller, 2011). The Initiative funded the establishment of 5,100 acres of switchgrass and a pilot biorefinery operated by DuPont Cellulosic Ethanol and Genera Energy Inc. Given the progress of the technology converting switchgrass to biofuel, the deployment of a larger-scale commercial biorefinery is under consideration.

The plant-gate cost of switchgrass feedstock could be significant to a biorefinery. The bulky nature of switchgrass makes it relatively expensive to harvest, store and transport considering its energy content. Switchgrass is harvested in a limited period of the year so the requirements for feedstock storage can be enormous and costly. In addition, weathering and precipitation during storage will lead to switchgrass dry matter losses and add to the cost of storage (Mooney et al., 2012). The opportunity cost of converting cropland to switchgrass production will also influence the willingness of farmers to grow switchgrass. Finally, the cost of switchgrass at the biorefinery plant-gate will also be affected by the production, harvest and transportation practices adopted, e.g., large round bale or large rectangular bale systems.

Activities in a switchgrass supply chain will produce GHG emissions that are different from current land use activities. Land use change can lead to GHG flux change as different crops have different soil carbon sequestration rates. In addition, with various N fertilizer application rates and application methods, the N$_2$O emissions from different crops are also varied. The application of fertilizer and herbicide, utilization of farm machinery for switchgrass production, and the production of those chemicals and equipment will all create GHG emissions. Moreover, transportation of switchgrass to the biorefinery will generate GHG emissions. GHG emissions from changes in land use are potentially spatially oriented as soil type and quality could vary considerably among regions. The availability of land for switchgrass production and transportation infrastructure may also be varied by region.

The potential impacts of various factors, such as land use change, harvested methods, storage loss, and regional infrastructure on the economic and environmental performance of a LCB feedstock supply chain have been examined in the literature (e.g. James et al., 2010; Searchinger et al., 2008; Spatari et al., 2005; Qin et al., 2011; Hess et al., 2007; Mooney et al., 2012; Kumar and Sokhansanj, 2009; Emery and Mosier, 2012; Qin et al., 2006; Jappinen et al., 2013; Archer and Johnson, 2012). Various studies included those factors in mathematical optimization or simulation models to evaluate the
designs of optimal LCB supply chain. Some researchers evaluated the optimal design of a LCB supply chain from the perspective of economic gains (e.g. Dunnett, et al., 2007; Kondili, et al., 1993; Mas, et al., 2010); while research considering both economic and environmental factors has also received recent attention (e.g. Bernardi, et al., 2012; Elia, et al., 2011; You, et al., 2012). Most of those aforementioned studies primarily focus on the performance of LCB feedstock supply chain from a macro perspective for a state or regional analysis. Evaluation of LCB feedstock supply chain based on a micro-level perception, which provides insights to the individuals who are interested in the emerging bioenergy industry, is generally lacking.

The goal of this study is to develop a feedstock supply chain for a potential commercial-scale biorefinery in Tennessee that optimizes both economic cost and GHG emissions. Since some factors such as land conversion and harvest/storage system have an effect on both the economic cost and GHG emissions, a trade-off might exist between these two objectives if one factor has a positive impact on cost [GHG emissions] while a negative influence on GHG emissions [cost]. This information is important since it can help both the government and investors develop a more balanced and sustainable bioenergy sector in the state and the southeastern region.

2. Methods and Data

A multi-objective geospatial mathematical programming model was developed to search for the Pareto-optimal solutions between cost and GHG emission in the supply chain of the dedicated energy crop (switchgrass) in Tennessee. The augmented $\varepsilon$-constraint method was used to for multi-objective optimization and generating the trade-off between these cost optimal and GHG emissions minimization. By integrating the criterions of economic (cost) and environmental (GHG emissions) factors in the objective function, the respective location of the biorefinery and feedstock draw area with different emphases on economic and environmental factors can be identified in the state. Also, based on the output of each determined location, a Pareto optimal between the cost and GHG emissions of feedstock supply chain to the biorefinery in the study area can be generated.

Following previous location studies integrating a multi-objective model and geographical information systems (e.g. Diamond and Wright, 1988; Jankowski, 1995; Laaribi, et al., 1996), the location of the biorefinery plant and associated feedstock draw area in Tennessee was also determined through applying the multiobjective model to high resolution spatial data. Figure 1 presents the potential feedstock draw area and industrial parks suitable to the biorefinery. All cropland in Tennessee and the area within 50 miles of the state boundary was decomposed into five square mile hexagons, so called crop zone, as the potential feedstock supply area. For each candidate industrial park, four optimization
scenarios were obtained: cost minimization and GHG emission-minimization were used as the two end points.

It was assumed that the capacity of the biorefinery is 50 million gallon per year with a biofuel conversion rate of 76 gallons per dry ton of switchgrass (Wang, et al., 1999). Switchgrass was assumed to be harvested from November to February during the production year and stored at the edge of the field for transportation. Two options for harvest, large round bale and large square bale, were assumed in the model. With different bale type and storage methods, different dry matter loss rates were considered. Truck was the mode considered for switchgrass haulage.

Table 1 listed the cost and emission components of the switchgrass supply system considered in this study, including the establishment, production, harvest, storage, and transportation of switchgrass. When assessing the economic cost, the profit of the existing crop before land conversion was considered as the opportunity cost. Production cost includes the expenses of switchgrass establishment and annual maintenance. The harvest, storage and transportation costs were primarily composed of the ownership and maintenance cost of equipment, labor usage, and fuel consumption. Storage cost also considered the materials of protection such as tarp and pallet. GHG emissions from the switchgrass supply chain were categorized into direct and indirect emissions. Direct emissions resulted from the land use change,
nitrogen fertilizer application, fuel usage, dry matter loss during storage, and transportation. Indirect emissions were caused by the production of seed, fertilizer, herbicide and machinery.

Table 1: Components of Cost and GHG Emission in a Switchgrass Supply Chain

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<thead>
<tr>
<th>Economic Cost</th>
<th>GHG emissions</th>
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<tr>
<td></td>
<td>Direct</td>
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<tr>
<td>Land Conversion</td>
<td>Opportunity Cost</td>
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<tr>
<td>Production</td>
<td>Establishment</td>
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<tr>
<td></td>
<td>Annual maintenance</td>
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<td></td>
<td>Farm machine: (fuel, labor, maintenance &amp; ownership)</td>
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<tr>
<td>Harvest</td>
<td>Fuel usage</td>
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<td>Storage</td>
<td>Labor</td>
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<td></td>
<td>Pickup fuel</td>
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<td></td>
<td>Tarps and pallets</td>
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<td>Transportation</td>
<td>Labor</td>
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<td></td>
<td>Fuel</td>
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3. Results and Discussion

Figure 2 shows the possible outcome from the multi-objective optimization and the Pareto optimal curve. The orange curve is the Pareto-optimal that represents the solutions which were not outperformed by any other sites with lower cost and lower GHG emissions. Those combinations along the curve reach Pareto efficiency indicate that an improvement in one objective (e.g. cost) needs to sacrifice the other one (e.g. GHG emissions). Any choices above the curve were sub-optimal. For the cost-minimal candidate A, the total cost of the supply chain was $45,975,322 (about $70/ton) and the GHG emissions were 81,588 CO₂e ton (124 CO₂e kg per tonnage). When GHG emissions were minimized in the candidate B, emissions were reduced by 64% to 45 CO₂e kg/ton. Meanwhile, total cost of the switchgrass chain nearly doubled to $85,344,344 ($130/ton). The tradeoff relationship between the two objectives is not linear. The candidate C in Figure 2 was a potential optimal location considering both objectives. Comparing to the cost minimization candidate A, the cost of switchgrass supply chain in the alternative optimal site C was about 9% higher ($76 vs. $70 per ton), while GHG emissions was cut to more than half from 124 CO₂e kg/ton to 61 CO₂e kg/ton. Similarly, comparing to the emission minimal site B, the GHG emissions created from feedstock supply system in candidate C increased by 27% but associated cost was 41% lower.
Differences among the profitability of crops replaced by switchgrass and soil carbon sequestration rates were the primary factors influencing the results for the two optimization criteria. Land conversion from hay to switchgrass had a low opportunity cost while crop-to-switchgrass was expensive. On the other hand, output from DAYCENT model indicated that hay had higher soil carbon sequestration rates than switchgrass while all other crops had lower carbon sequestration rates. This indicates by choosing the type of land conversion, we can achieve high economic efficiency with more GHG emissions, or less GHG emissions with higher economic cost.

Figure 3 shows the location of the biorefinery and feedstock draw area for the three candidates. Candidate A, the cost minimal site, was located in Rutherford County. The majority of the supply region was converted from hay while a small portion was from cropland such as cotton, wheat and soybean. Under GHG emission minimization, candidate B was suggested to be in Obion County where the entire feedstock supply was converted from cropland. With both objectives were taken into account, the biorefinery was located in Haywood County (candidate C). About 16% of the supply region was converted from hay land. The location of the biorefinery and the layout of the supply regions are affected by land availability and land type. The West Tennessee region near the Mississippi River has large tracts of plains suitable for crop production, while more hay land are available in Middle and East Tennessee. The cost minimal location for biorefinery, therefore, is located in Rutherford County in the Middle Tennessee while the GHG emission minimal location lies in Obion County in the west.
Figure 4 summarizes the cost and GHG emissions of those three sites. Land conversion is the major factor contributing to the differences in costs and GHG emissions between those candidate sites. For the cost minimal site A, the opportunity cost for land conversion accounted for 3.5% of the total cost of feedstock supply chain, whereas it made up to 50% of the total cost for the GHG emissions minimal site B. In terms of GHG emissions, the soil carbon emissions from land use change were 25,000 CO₂e ton, about 31% of the total GHG emission, for the candidate site A as more than 95% of the supply region was converted from hay. In contrast, a net soil carbon sequestration of 26 thousand CO₂e ton was obtained from land use change for candidate site B since all switchgrass area was converted from cropland. A more balanced combination of land conversion from hay land and cropland was observed for the alternative optimal site C on the Pareto curve. The associated opportunity cost from land use change was only 13% of the total cost of feedstock supply chain while 17,000 CO₂e ton carbons were sequestrated from land conversion.
4. CONCLUSION

Establishing a domestic bioenergy industry and reduce carbon emissions from energy production and consumption are among the current strategic plans of the Office of Energy Efficiency and Renewable Energy in the U.S. Department of Energy. Obviously, economic feasibility is the major focus in the development of this emerging industry; however, environmental factor is also important when targeting a sustainable bioenergy sector. As the development of bioenergy is involved in both agricultural and energy sectors, both the cost and GHG emissions resulting from land use change, farm operations and transportation in the supply chain of energy crops certainly need to be taken into account in the evaluation.

Our findings suggest that the cost of biofuel feedstock supply system is sensitive to the land that goes into the production of the feedstocks required by the bioenergy industry. Also, considering additional criteria of environmental performance will result in increased feedstock costs, which may dampen the industry’s willingness to incorporate the environmental criteria in the decision of biorefinery location. However, assistance from the government could encourage the industry to locate the biorefinery
in a location to mitigate GHG emissions from land use change for feedstock production and lead to a more environmental friendly biofuel sector. The Pareto curve derived from this study implies that the GHG emissions from land use for feedstock production can be reduced considerably through reasonable incentives from the government to the biofuel industry.
References


