Lignocellulosic Biomass Harvest and Delivery Cost

Lawrence Mapemba and Francis M. Epplin

Lawrence Mapemba is a graduate research assistant and Francis M. Epplin is a professor in the Department of Agricultural Economics, Oklahoma State University, Stillwater. The authors thank personnel of the Biobased Products and Energy Center at Oklahoma State University for assistance. This material is based upon work supported in part by Aventine Renewable Energy, Inc., USDA-CSREES IFAFS Competitive Grants Program award 00-52104-9662, USDA-CSREES Special Research Grant award 01-34447-10302, and the Oklahoma Agricultural Experiment Station. Support does not constitute an endorsement of the views expressed in the paper by Aventine Renewable Energy or by the USDA. Professional paper AEP-0401 of the Oklahoma Agricultural Experiment Station, Project H-2403.

Selected Paper prepared for presentation at the Southern Agricultural Economics Association annual meetings, Tulsa, Oklahoma, February 14-18, 2004.

Contact author:
Francis M. Epplin
Department of Agricultural Economics
Oklahoma State University
Stillwater, OK 74078-6026

Phone: 405-744-7126
FAX: 405-744-8210
e-mail: epplin@okstate.edu

Lignocellulosic Biomass Harvest and Delivery Cost

Abstract

The logistics of providing an orderly flow of lignocellulosic feedstock to a biorefinery have not been addressed by most biorefinery feasibility studies. A mixed integer mathematical programming model is developed that includes integer decision variables enabling investment in harvest machines that provide monthly harvest capacity based upon expected harvest days.

Introduction

From 1993 to 2002, U.S. ethanol production increased from 1.15 billion gallons to 2.13 billion gallons. Production was expected to increase to more than 2.7 billion gallons in 2003 (Renewable Fuels Association). Corn grain is the primary feedstock used to produce ethanol in the U.S. But, the high cost of corn, relative to the selling price of ethanol, and uncertain markets for some of the protein co-products has led to increased interest in lignocellulosic biomass (LCB) feedstock for ethanol production (O'Brien et al.). Tembo, Epplin, and Huhnke contend that ethanol-conversion technology is relatively most efficient with plants that have high cellulose content such as grasses, crop residues and trees compared to corn grain. The primary problem of ethanol's production in the U.S. has been and still remains economic, as evidenced by federal and state ethanol subsidies. Conversion technologies used in grain-based biorefineries are approaching their inherent theoretical limits.

Alternative methods for producing biobased products including ethanol have been developed that are based upon the use of low valued LCB such as crop residue and perennial grasses. Agricultural residues (e.g. corn stover, crop straw, sugarcane bagasse), herbaceous crops (e.g. alfalfa, switchgrass, perennial grasses), forestry residues, and other woody biomass, wastepaper, urban wastes and other wastes, could be used as LCB feedstock (Wyman).

Theoretically, an LCB-based system could be much more efficient than conversion of corn grain since most of the harvested plant material could be used.

A major potential advantage of LCB gasification fermentation biorefining technology is that a variety of feedstocks, including agricultural residues (such as corn stover and wheat straw), native perennial grasses, introduced perennials such as fescue and bermudagrass, and dedicated energy crops such as switchgrass may be refined by the same facility. Use of a variety of feedstocks has many potential advantages. Harvest windows differ across species enabling the use of harvest and collection machinery throughout many months and reducing the fixed costs of harvest machinery per unit of feedstock.

Unlike corn grain, a well-developed harvesting and transportation system does not exist for LCB. While some farmers have harvest machines and equipment that might be used to harvest LCB, it is unlikely that most regions would have a sufficient investment in harvesting machinery that could provide massive quantities of LCB in a consistent package and provide an orderly flow of LCB to a biorefinery throughout the year.

A number of studies have provided estimates of LCB production costs (English, Short, and Heady; Cundiff and Harris; Glassner, Hettenhaus and Schechinger; Gallagher and Johnson; Nienow et al.; Walsh). Walsh reported that LCB production cost estimates range from $24 per ton to more than $121 per ton depending upon crop, region, yield, and method of analysis. Based upon a survey of custom harvest charges, Kletke and Doye reported an average charge of $23 per ton for cutting, raking, and baling forage. Comparisons across studies are difficult because of differences in assumptions and methods. However, two consistent patterns across studies is that (i) a single point estimate is reported independent of the assumption about the size or number of tons harvested per year by the assumed set of machines and (ii) the lack of an existing harvesting infrastructure has received little attention.

This research attempts to provide insight on LCB harvest costs. The specific objective is to determine the extent to which the method of accounting for LCB harvest costs changes the estimated cost to produce a gallon of ethanol. Results from a conventional model that includes a fixed harvest charge per ton are compared to those of an alternative model that includes an integer investment activity such that the number of harvest machines is endogenously determined. In this alternative configuration of the model, monthly harvest capacity constraints are included to restrict the number of tons harvested per month to not exceed the available capacity that depends upon the endogenously determined number of harvest machines and the number of harvest days.

Procedures

This study builds upon the work of Tembo and Thorsell. Both Tembo and Thorsell assumed LCB gasification fermentation biorefining technology that enables processing of a variety of feedstocks by the same facility. Tembo developed a model of Oklahoma's potential for economic bioconversion of LCB feedstock. Tembo's model differed from prior studies in several respects. His model and case study considered (i) a variety of feedstocks; (ii) recognized that an LCB biorefinery would require a steady flow of feedstock and broke the year into 12 discrete periods (months); (iii) recognized that different feedstocks have different harvest windows and that the dry matter yield of species depends upon the time (month) of harvest; (iv) recognize that storage losses will occur and depend upon location of storage and time of storage; and (v) included multiple biorefinery sizes and locations that enabled investigation of the tradeoff between economies of biorefinery size and feedstock transportation costs. Tembo's model was designed to determine the number, size and distribution of LCB-based biorefinery processing capacity that maximizes industry net present worth, the optimum quantities of LCB stocks and flows, and the most important cost items in the system.

Tembo used conventional agricultural machinery cost estimation software to compute costs on an acre rather than ton harvested basis. He computed and used a charge of $7.30 per acre for wheat straw, $12.30 per acre for corn stover, old world bluestem, native tall, native mixed, native short, bermudagrass, tall fescue, and $24.29 per acre for switchgrass. These charges were assessed independent of yield. Tembo did not place any restrictions on the number of acres that could be harvested during a time period. His method results in two potential problems. First, harvest costs varied by ton since they were fixed per acre for each species independent of expected yield. For example, the cost to harvest an acre of native prairie grass was estimated to be $12.30. Estimated yields of prairie grasses varied across regions from 0.67 to 3.0 tons per acre. Hence, the estimated cost to harvest a ton of prairie grass ranged from $4.10 to $18.35. A second potential problem with Tembo's method is that based upon the assumptions, the model determined that it was optimal to harvest more than 80% of total LCB tonnage required for an entire year in the month of September. A large investment in harvest machines would be required to achieve the capacity necessary to harvest the quantity of required LCB in a short time period. The machines would be idle for most of the year.

Thorsell, in cooperation with agricultural engineers, designed a coordinated harvest unit that provides a capacity to harvest a given number of tons per time period. The harvest unit includes ten laborers, nine tractors, three mowers, three rakes, three balers, and a field transporter. For her estimate of machinery requirements and cost, it was assumed that the speeds and windrow widths can be adjusted with yield to maintain a relatively constant machine throughput capacity. She reports that the annual capacity of the defined harvest unit is 54,839 tons of LCB and the total cost of using one harvest unit at capacity is estimated to be $580,000 per year. Her estimate reflects substantial economies of size. An estimate of a harvest cost per ton of LCB could be obtained by dividing the per-year cost of a harvest unit, $580,000, by the per-year harvest capacity of a harvest unit, 54,839 tons of LCB, to obtain a fixed harvest charge of $10.58 per ton of LCB. This cost estimate is based upon the assumption that LCB could be harvested from June through February and that the harvest unit is used to capacity during each of the nine harvest months.

This study differs from prior studies in several respects. First, in the present study the harvest unit with throughput capacity as designed by Thorsell is incorporated into the Tembo model as an integer activity that for an annual cost (depreciation, insurance, interest, taxes, repairs, fuel, oil, lubricants, and labor) provides capacity to harvest a given tonnage per harvest day. A single harvest unit provides a capacity of 340.67 tons per day. Monthly capacity depends upon the number of harvest days per month. Second, an estimate of the expected number of harvest days per month based upon historical weather is incorporated. Third, Tembo's multi-region, multi-period, mathematical programming model is modified in several ways. For what is herein described as a conventional model, Tembo's harvest charge per acre is replaced with a harvest charge per ton of $10.58 for all species. For the alternative model, Tembo's model is modified by including an integer investment activity that enables the model to invest in the optimal number of harvest units as defined by Thorsell. In this configuration of the model, monthly harvest capacity constraints are included to restrict the number of tons harvested per month to not exceed the available capacity provided by the endogenously determined number of harvest units and the number of harvest days.

Following Tembo, Epplin, and Huhnke, the objective function of the multi-region, multi-period, mixed integer investment appraisal model with a harvest cost per ton is given as:

$$\begin{aligned}\underset{q,x,xt,xs,A}{\text{Max}} \quad NPW = \Bigg\{ \sum_{m=1}^{12} \Bigg[& \sum_{j=1}^{11}\sum_{s=1}^{3}\sum_{g=1}^{4} \rho_g q_{jsgm} - \sum_{i=1}^{77}\sum_{k=1}^{10}\sum_{f=1}^{5} \alpha_k A_{ikfm} - \sum_{i=1}^{77}\sum_{k=1}^{10} \gamma_k xs_{ikm} \\ & - \sum_{i=1}^{77}\sum_{j=1}^{11}\sum_{s=1}^{3}\sum_{k=1}^{10} \tau_{ij} xt_{ijskm} - \sum_{i=1}^{77}\sum_{k=1}^{10}\sum_{f=1}^{5} \varphi_k x_{ikfm} \Bigg] \\ & - \sum_{j=1}^{11}\sum_{s=1}^{3}\sum_{ft=1}^{2} TAFC_{s,ft}\,\beta_{js} \Bigg\} * PVAF \end{aligned} \tag{1}$$

where quantity of process outputs (*q*), acres of LCB harvested (*A*), tons of LCB stored in the field (xs_{ikm}), tons of LCB transported between production regions and biorefinery locations (*xt*) are choice variables, and NPW is the net present worth of the industry. For each prospective plant location and size, $\beta_{js} \in \{0,1\}$ are binary choice variables, equal to one if a plant of size *s* is optimum at location *j* and zero otherwise, where *s* = {1, 2, 3} and *j* = {1, 2,…, 11}. Subscripts *i* = {1, 2,.., 77}, *g* = {1, 2,…, 4} and *f* = {1, 2, …, 5} index LCB production region, product type and level of fertilizer applied to the harvested LCB acres, respectively. The type of facility at the plant (for processing or storage), the species of LCB feedstock and the monthly planning periods are indexed as *ft* = {1, 2}, *k* = {1, 2,…, 10 }, and *m* = {1, 2,…, 12}, respectively. *TAFC* is the amortized annual cost of constructing and operating a biorefinery. *PVAF* is the present value of annuity factor, which is given as $PVAF = \frac{(1+r)^T - 1}{r(1+r)^T}$, where *T* is useful plant life in years, and *r* is the discount factor.

Output price, ρ_g, may be positive for biorefinery outputs such as ethanol, acetic acid, or a positive externality, or negative when *g* is a negative externality. Parameters α, γ, and τ represent unit cost of producing LCB on leased land, cost of storing a ton of LCB for one month, and unit cost of transporting a ton of LCB from production region *i* to biorefinery *j*, respectively. φ_k is the fixed charge per ton of LCB of species *k* harvested and x_{ikfm} is the quantity of LCB *k* under fertility level *f* harvested from region *i* in month *m*.

Equation (1) is maximized, subject to several system constraints. Land constraints are imposed as:

$$(2) \qquad \sum_{f=1}^{5}\sum_{m=1}^{12} A_{ikfm} - \sum_{l=1}^{L} BP_{ikl} * LAND_{ikl} \leq 0, \qquad \forall i, k,$$

where $LAND_{ikl}$ is total acres of land suitable for production of LCB feedstock *k* at production region *i*, which includes land currently under *k* and/or, if permissible, land displaced from other existing cropping activities. Subscript $l = \{1, 2, \ldots, L\}$ indexes the categories of land suitable for *k* if more than one. The variable *BP*, $0 \leq BP \leq 1$, limit the portion of available land that can be harvested for LCB feedstock in each production region.

The quantity (tons) of each LCB species available for delivery to biorefineries from the harvested acres is computed as:

$$(3) \qquad \sum_{f=1}^{5} x_{ikfm} - YAD_{km} * \sum_{f=1}^{5} A_{ikfm} BYLD_{ikf} = 0, \qquad \forall i, k, m,$$

where *x* is quantity of harvested LCB in tons, *BYLD* is potential yield (tons per acre), and *YAD* is yield adjustment factor. *YAD* varies from zero to one, depending on quantity and quality variations by month of harvest, with the highest value (equal to one) at optimal harvest times. An additional constraint is imposed to ensure no acres are harvested when $YAD = 0$:

$$(4) \qquad \sum_{f=1}^{5} A_{ikfm} = 0 \qquad \text{if } YAD_{km} = 0, \qquad \forall i, k, m.$$

To ensure no more LCB is shipped from any production region than is actually available at the time of shipment, the following constraint is imposed:

(5) $$\sum_{j=1}^{11}\sum_{s=1}^{3} xt_{ijskm} + xs_{ikm} - \theta_{ik} xs_{ikm-1} - \sum_{f=1}^{5} x_{ikfm} \leq 0 \qquad \forall i,k,m,$$

where *xt* represents tons of LCB shipped from region *i* to biorefinery *j*. The parameter θ_{ik} is the proportion of biomass *k* which is usable following one month of in-field storage at production region *i* and is computed as $\theta_{ik} = 1 - dt_{ik}$, where dt_{ik} is monthly deterioration rate for LCB feedstock species *k* when stored at production region *i*. Equation (5) tells the model that, in each month and at each source, the sum of quantity shipped to plants and quantity put in storage of each LCB feedstock, *k*, cannot exceed the sum of current production and usable portion of stored biomass. No storage upper bounds are assumed for in-field storage.

Equation (6) stipulates that quantity of LCB shipped out plus LCB lost in in-field storage balance with total LCB produced in the year, that is:

(6) $$\sum_{f=1}^{5}\sum_{m=1}^{12} x_{ikfm} - \sum_{j=1}^{11}\sum_{s=1}^{3}\sum_{m=1}^{12} xt_{ijskm} - (1-\theta_{ik}) * \sum_{m=1}^{12} xs_{ikm} = 0, \quad \forall i,k,$$

where all the variables and parameters are as previously defined.

At each plant, the respective capacity constraints for processing and on-site LCB storage are defined as:

(7) $$q_{jsem} - CAPP_s \beta_{js} \leq 0, \qquad \forall j,s,m, \qquad \text{and}$$

(8) $$\sum_{k=1}^{10} xs_{jkm} - CAPS_s \beta_{js} \leq 0, \qquad \forall j,s,m,$$

where *CAPP* is monthly processing capacity and *CAPS* is on-site storage capacity in tons of LCB per month.

The model is structured with monthly periods. In each planning period (the month), total quantity of LCB available at each plant may not exceed the sum of all the LCB transported to the plant and the undeteriorated portion of the LCB stored on-site from the previous month:

$$(9) \qquad \sum_{i=1}^{77} xt_{ijskm} + \phi_{jk} xs_{jkm-1} - xs_{jkm} - xp_{jskm} \geq 0, \qquad \forall j,k,m,s,$$

where xs_{jkm} denotes tons of LCB feedstock *k* stored at biorefinery location *j* in month *m*, and *xp* is the quantity of LCB processed at the plant. The parameter ϕ_{jk} is the proportion of biomass *k* that is usable following one month of on-site storage at biorefinery location *j* and is computed as $\phi_{jk} = 1 - dt_{jk}$, where dt_{jk} is monthly deterioration rate for feedstock species *k* when stored at biorefinery location *j*.

Similar to equation (6), equation (10) imposes annual balance between total LCB shipped to the biorefinery and the sum of LCB processed and the LCB lost in on-site storage:

$$(10) \qquad \sum_{i=1}^{77} \sum_{m=1}^{12} xt_{ijskm} - (1-\phi_{jk}) * \sum_{m=1}^{12} xs_{jskm} - \sum_{m=1}^{12} xp_{jskm} = 0, \quad \forall j,k,s,$$

where all the variables are as previously defined. To ensure no unexpected LCB supply interruptions occur during any of the planning periods, a minimum LCB inventory level can be imposed for each plant, that is:

$$(11) \qquad \sum_{k=1}^{10} xs_{jkm} - MBINV_s \geq 0, \qquad \forall j,m,s,$$

where $MBINV_s$ is minimum biomass inventory for plant size *s*. An appropriate production function must be used to model transformation from raw materials (biomass) to end products (biobased products) and by-products. If we assume a Leontief production function (fixed input-output coefficients), for example, the output supply constraint can be expressed as:

$$(12) \qquad q_{jsgm} - \sum_{k=1}^{10} \lambda_{kg} xp_{jskm} \leq 0, \qquad \forall g,j,m,s,$$

which imposes a direct fixed-proportion relationship between processed biomass, *xp*, and each of the outputs. The parameter λ is a vector of process input-output coefficients, in units of output (ethanol) or byproduct (CO_2, N_2 or Ash) per ton of LCB. The inequality in equation (12) enables allowance for production losses.

A Leontief production possibilities frontier is imposed between the bioproduct and each by-product, designated by:

$$q_{jsem}\lambda_{kg} - q_{jsgm}\lambda_{ke} = 0, \qquad \forall g, j, k, m, s. \tag{13}$$

Equation (13) also implies that any quantity of bioproduct produced would result in a corresponding amount of the by-products. These by-products may have positive or negative value. At most one plant is permitted at each location:

$$\sum_{s=1}^{3} \beta_{js} \le 1, \qquad \forall j, \tag{14}$$

where the variable β_{js} is as previously defined. The eleven prospective biorefinery locations were selected based on concentration of LCB production and availability of road infrastructure. If a particular location is optimal, both processing and onsite LCB storage facilities need to be constructed. Choice of optimum plant size from among three options, s = {small, medium, large}, is influenced to a great extent by size economies. Finally, nonnegativity conditions are imposed on choice variables. That is, acres harvested, all biomass variables, and all output levels are restricted to be nonnegative:

$$A_{ikfm}, x_{ikm}, xs_{ikm}, xs_{jkm}, xt_{ijskm}, xp_{jskm}, q_{jsgm} \ge 0. \tag{15}$$

The objective function for the alternative model that includes an integer harvest unit activity rather than a harvest cost per ton is specified as:

$$\begin{aligned} \underset{q,x,xt,xs,A}{\text{Max}} \quad NPW = \Bigg\{ \sum_{m=1}^{12} \Bigg[& \sum_{j=1}^{11}\sum_{s=1}^{3}\sum_{g=1}^{4} \rho_g q_{jsgm} - \sum_{i=1}^{77}\sum_{k=1}^{10}\sum_{f=1}^{5} \alpha_k A_{ikfm} - \sum_{i=1}^{77}\sum_{k=1}^{10} \gamma_k xs_{ikm} \\ & - \sum_{i=1}^{77}\sum_{j=1}^{11}\sum_{s=1}^{3}\sum_{k=1}^{10} \tau_{ij} xt_{ijskm} \Bigg] - \sum_{j=1}^{11}\sum_{s=1}^{3}\sum_{ft=1}^{2} TAFC_{s,ft}\beta_{js} - \delta HU \Bigg\} * PVAF, \end{aligned} \tag{16}$$

where HU is a coordinated set of harvest machinery with labor (known as a harvest unit) and δ is the annual ownership and operating cost of one harvest unit. All other variables are as defined above. This alternative model includes monthly harvest unit capacity constraints:

$$\text{(17)} \qquad \sum_{i=1}^{77}\sum_{k=1}^{10}\sum_{f=1}^{5} x_{ikfm} - (HU * CAPHU_m) \le 0, \qquad \forall m,$$

where $CAPHU_m$ is the capacity of a harvest unit in tons of LCB in month m. The alternative model also requires that the harvest unit activity be an integer.

(18) HU is integer.

Given some base values of all parameters, the above model determines base solution for the conventional model by maximizing equation (1), subject to equations (2) through (15). For the alternative model, equation (16) is maximized subject to equations (2) through (15) plus equations (17) and (18). GAMS/CPLEX was used to solve the models (Brooke et al., 1998).

Data

The two models maximize the net present worth of an LCB gasification-fermentation industry over a 15-year period with a 15% discount rate. The models include each of Oklahoma's 77 counties as potential LCB production sources; 11 potential biorefinery locations; nine potential feedstock species; three potential biorefinery sizes (25, 50 and 100 million gallons of ethanol per year); ethanol as a single product priced at \$1.25 per gallon; and 33 binary variables to accommodate the possibility of one of three potential biorefinery sizes in each of 11 potential locations. For additional data information, including available acres, expected yields by month of harvest by feedstock, expected storage losses, and production, storage, transportation, and processing costs see Tembo and Tembo, Epplin, and Huhnke.

Reinschmiedt estimated probability distributions of the number of field-workdays available in Oklahoma by month. Thorsell used the field workday probability distributions and assumed that harvest could occur on a field workday. She selected the number of days associated with the 95% level on the probability distributions as an estimate of the number of harvest days per month. In other words, based upon the probability distributions, in 19 of 20 years the number of harvest days per month would be expected to equal or exceed the number that she used to determine monthly harvest capacity of the harvest unit.

Tembo found that in Oklahoma wheat straw may be harvested in June and July and corn stover in September and October. Harvest of perennial grasses could begin as early as July and continue for an extended period to as late as February. Perennial grasses such as switchgrass may be permitted to mature in the field and be harvested as late as February of the following year. A variety of feedstock enables an extended harvest system from June through February of the following year. For detailed information about development of the harvest unit, see Thorsell.

Results

The specific objective was to determine the extent to which the method of accounting for LCB harvest costs changes the estimated cost to produce a gallon of ethanol. To achieve this objective, four models were formulated and solved. These are labeled in Tables 1 and 2 as (i) conventional harvest cost per ton; (ii) integer harvest units; (iii) breakeven-conventional harvest cost per ton; and (iv) breakeven-integer harvest units. For the conventional harvest cost per ton model, a harvest charge of $10.58 per ton was assessed for all tons harvested. For the integer harvest units model, an integer investment activity was included such that the number of harvest units was endogenously determined. In this alternative configuration of the model, monthly harvest capacity constraints were included to restrict the number of tons harvested per month to not exceed the available capacity that depends upon the endogenously determined number of harvest units and the number of harvest days. A harvest unit as defined, provides a capacity of

54,839 tons per year allocated across months depending upon harvest days per month and has an annual cost of $580,000.

Breakeven models were solved for both the conventional harvest cost per ton and the integer harvest units scenarios. For the breakeven models, a grid search procedure was implemented to determine the ethanol price level at which net present worth is equal to zero. Table 1 includes selected results from the conventional harvest cost per ton model. Five large (100 million gallons per year) biorefineries would optimally process 6.7 million tons of LCB annually harvested from 2.49 million acres of land giving an expected net present worth of $916.8 million. LCB is harvested from each of the nine potential feedstocks.

Based on the assumptions of the integer harvest units model, four large (100 million gallons per year) biorefineries would optimally produce 400 million gallons of ethanol with an expected net present worth of $811.7 million (Table 2). The four biorefineries would process 5.3 million tons of LCB annually, harvested from 1.998 million acres.

When the problem is modeled under the assumption of coordinated harvest units that are constrained by available field workdays, the expected net present worth is lower than when a conventional harvest cost per ton is assumed. The difference in net present worth between the integer harvest units model and the model with a conventional harvest cost per ton is about $105.09 million. The integer harvest units model has one less biorefinery compared to the model with a conventional harvest cost per ton. These results suggest that a model that does not consider harvest day constraints may overstate the value of an LCB gasification-fermentation industry.

Table 2 includes the level of costs incurred to produce a gallon of ethanol. For the integer harvest unit's model, the total costs are estimated to be $0.90 per gallon. The major cost items are biorefinery investment, maintenance, and operation costs (42%), followed by land rental costs and feedstock transportation costs (both at 18% of the total), and then harvest costs (16%).

These results show that harvest costs ($0.14 per gallon) constitute 27% of the total cost to deliver ($0.58 per gallon) LCB feedstock to a biorefinery. This is equivalent to $43.50 per delivered dry ton of LCB. These findings are consistent with those reported elsewhere. Cundiff and Harris found that harvest cost alone constituted 46% of total LCB delivery cost. Epplin found that the maintenance and harvest cost were 32% of LCB delivery cost. Cundiff estimated that harvest cost was almost half of the total cost to deliver LCB to a biorefinery.

For the fixed charge model, the total costs are estimated to be $0.94 per gallon (Table 2). The higher total costs per gallon in this model compared to the integer harvest unit model are due to the added biorefinery. As more biorefineries are "constructed", the average cost to deliver a ton of LCB feedstock increases. The major cost items in the fixed harvest cost model are plant costs (41%), followed by transportation costs (18%), then land rental costs (17%), and then harvest costs (15%).

From the results of the grid search for a threshold price of ethanol, it was determined that the breakeven price of ethanol for the integer harvest units model would be about $0.85 per gallon and for the conventional harvest cost per ton scenario would be $0.84 per gallon. For both of the breakeven scenarios, one large (100 million gallons per year) biorefinery would be optimal. For the integer harvest unit case scenario, the plant will process 1.3 million tons of LCB annually, harvested from 425 thousand acres of land. On the other hand, for the conventional harvest cost per ton scenario, the plant will equally process 1.3 million tons of LCB annually, harvested from 436 thousand acres of land (Table 2). In both the integer harvest unit and the conventional harvest cost per ton scenarios, the major cost items will be plant costs (45%), transportation costs (19% for integer harvest units and 20% for the conventional harvest cost per ton scenario), harvest cost (17%), and land rental cost (14%).

Figures 1 and 2 contain charts of the estimated optimal LCB tons harvested by month for each scenario. Figure 1 indicates that when monthly harvest capacities are not imposed, harvest is concentrated in November and December. And, to harvest the estimated November LCB quantity a total of 276 harvest units would be required. Whereas, when monthly harvest capacities are imposed, the integer harvest units model determines that it is optimal to only have 98 harvest units and to use them at near capacity to harvest a variety of feedstocks throughout the nine month harvest season.

Thorsell estimated that a harvest unit would require an average capital investment of approximately $590,000. Average investment is defined to be half of the sum of the purchase price plus salvage value for each machine summed across all 19 machines in the defined harvest unit. Based upon this estimate, 98 harvest units would require an average investment of $57.82 million. Whereas 276 harvest units would require an average investment of $162.84 million. Clearly, ignoring the influence of weather on the ability to harvest LCB feedstock can have substantial economic consequences.

Conclusion

The lack of an established infrastructure for LCB feedstock harvest and storage has received little attention in prior studies of the economics of a LCB biorefinery. The specific objective of this study is to determine the extent to which the method of accounting for LCB harvest costs changes the estimated cost to produce a gallon of ethanol. Two methods were used in the study, in one method, timing of harvest was ignored and a fixed charge per ton was assessed; in the second method, harvest machinery investment integer activities were included. The machinery investment activities provided varying levels of harvest capacity per month depending upon estimates of expected harvest hours per month. Results from the conventional model that includes a fixed harvest charge per ton are compared to those of an alternative model that includes an integer investment activity such that the number of harvest machines is endogenously determined. In this alternative configuration of the model, monthly harvest capacity constraints are included to restrict the number of tons harvested per month to not exceed the available capacity that depends upon the endogenously determined number of harvest machines and the number of harvest days.

Assumptions about the harvest structure of LCB feedstock in LCB biorefinery economic analysis could greatly affect the results and conclusions drawn from the study. The model that assumes a coordinated harvest structure with machinery and harvest crews and operating on time constraint due to differences in monthly field workdays could capture the true harvest cost and give more reliable results than an alternative model that assumes a conventional harvest cost per ton. LCB harvesting for biorefinery production requires machinery and harvest crews with capacity constraints. Models that incorporate harvest units are capable of modeling the harvest unit capacity endogenously.

References

Brooke, A., D. Kendrick, A. Meeras, and R. Raman. "General Algebraic Modeling System." GAMS Development Corporation, 1998. Available Online at http://www.gams.com/

Cundiff, John S. "Simulation of Five Large Round Bale Harvesting System for Biomass." *Bioresource Technology*, 56(1996): 77-82.

Cundiff, John S., and W. Lamar Harris. "Maximizing Output-Maximizing Profits."*Resource*, 2(1995):8-9.

English, Burton C., Cameron Short, and Earl O. Heady. "The Economic Feasibility of Crop Residues as Auxiliary Fuel in Coal-Fired Power Plants." *American Journal of Agricultural Economics*, 63-4(1981):636-644.

Epplin, Francis M. “Cost to Produce and Deliver Switchgrass Biomass to an Ethanol-Conversion Facility in the Southern Plains of the United States.” *Biomass and Bioenergy*, 11(1996): 459-467.

Gallagher, Paul and Donald Johnson. "Some New Ethanol Technology: Cost Competition and Adoption Effects in the Petroleum Market." *The Energy Journal,* 20-2(1999):89-120.

Glassner, David A., James R. Hettenhaus, and Thomas M. Schechinger. Corn Stover Collection Project. Paper presented at the Great Lakes Regional Biomass conference, BioEnergy '98 in Madison, Wisconsin, October 4-8, 1998. [Online] Available http://www.afdc.doe.gov/pdfs/5149.pdf.

Kletke, D., and D.G. Doye. 2002. Oklahoma farm and ranch custom rates, 2001-2002. Oklahoma Cooperative Extension Service, CR-205:1-9.

Nienow, S., Kevin T. McNamara, Andrew R. Gillespie, and Paul V. Preckel. “ A Model for the Economic Evaluation of Plantation Biomass Production for Co-firing with Coal in Electricity Production.” *Agricultural and Resource Economic Review* 28 April (1999): 106-118.

O’Brien, D.J., G.E. Senske, M.J. Kurantz, and J.C. Craig Jr. “Ethanol Recovery from Corn Fiber Hydrolysate Fermentation by Pervaporation.” *Bioresource Technology*, Article In Press.

Reinschmiedt, Lynn L., “Study of the Relationship Between Rainfall and Fieldwork Time Available and its Effect on Optimal Machinery Selection.” MS Thesis, Oklahoma State University, 1973.

Renewable Fuels Association (RFA). “Building a Secure Energy Future.” 2003 Available Online at http://www.ethanolrfa.org/outlook2003.PDF

Tembo, G. “Integrative Investment Appraisal and Discrete Capacity Optimization over Time and Space: The Case of an Emerging Renewable Energy Industry.” Ph.D. Dissertation, Oklahoma State University, Stillwater, Oklahoma, 2000.

Tembo, G., F.M. Epplin, and R.L. Huhnke. “Integrative Investment Appraisal of a Lignocellulosic Biomass-to-Ethanol Industry.” *Journal of Agriculture and Resource Economics* 28(2003):611-633.

Thorsell, S.R. “Economies of Size of a Coordinated Biorefinery Feedstock Harvest System.” Master’s Thesis, Oklahoma State University, Stillwater, Oklahoma, 2003.

Walsh, Marie E. “U.S. Bioenergy Crop Economic Analyses: Status and Needs.” *Biomass and Bioenergy,* 14(1998):341-50.

Wyman, C.E. “Ethanol Production from Lignocellulosic Biomass: Overview.” In *Handbook on Bioethanol: Production and Utilization*, ed. C.E. Wyman pp1-18. Taylor and Francis, Washington D.C., 1996.

Table 1. Selected Results including Tons Processed and Acres Harvested for each Scenario

Scenario	Net Present Worth (‘000$)	No. of Plants	Number of Harvest Units	Gallons of Ethanol (‘000)	Tons Processed (‘000)	Acres per Year (‘000)	No. of LCB Species
Conventional harvest cost per ton[a]	916,807	5	[b]	500,000	6,667	2,494	9
Integer harvest units[c]	811,719	4	98	400,000	5,333	1,998	8
Breakeven-Conventional harvest cost per ton	0[d]	1	[e]	100,000	1,333	436	4
Breakeven-integer harvest unit	0[d]	1	25	100,000	1,333	425	4

[a] A harvest charge of $10.58 per ton was assessed to all tons harvested.

[b] 276 harvest units would be required to harvest the estimated November LCB quantity.

[c] A harvest unit includes ten laborers, nine tractors, three mowers, three rakes, three balers, and a field transporter. It provides a capacity of 54,839 tons per year allocated across months depending upon harvest days per month and requires an average capital investment of approximately $590,000. The estimated annual ownership and operating cost of using one harvest unit at capacity is $580,000.

[d] A grid search procedure incremented the price of ethanol to determine the price level at which net present worth is equal to zero.

[e] 62 harvest units would be required to harvest the estimated February LCB quantity.

Table 2. Level and Percentage of Costs Incurred to Produce a Gallon of Ethanol by Scenario

Scenario	Cost by Item ($/gallon)[a] Land Rent	Field Costs[b]	Harvest Costs	In-field Storage	Transportation Costs	Plant Costs[c]	Total Costs
Conventional harvest cost per ton[d]	0.16 (17%)	0.06 (6%)	0.14 (15%)	0.04 (4%)	0.16 (18%)	0.38 (41%)	0.94 (100%)
Integer harvest units[e]	0.16 (18%)	0.04 (4%)	0.14 (16%)	0.02 (3%)	0.16 (18%)	0.38 (42%)	0.90 (100%)
Breakeven-Conventional harvest cost per ton[f]	0.12 (14%)	0.02 (3%)	0.14 (17%)	0.01 (1%)	0.17 (20%)	0.38 (45%)	0.84 (100%)
Breakeven-integer harvest units[f]	0.11 (14%)	0.02 (2%)	0.15 (17%)	0.02 (3%)	0.17 (19%)	0.38 (45%)	0.85 (100%)

[a] The values in parentheses are percentage of total cost per gallon of ethanol production. Values may not sum to 100% due to rounding error.

[b] All costs associated with establishing (for switchgrass only) and maintaining feedstock fields.

[c] All costs associated with construction, operation and maintenance of onsite storage and processing facilities.

[d] A harvest charge of $10.58 per ton was assessed to all tons harvested.

[e] A harvest unit includes ten laborers, nine tractors, three mowers, three rakes, three balers, and a field transporter. It provides a capacity of 54,839 tons per year allocated across months depending upon harvest days per month and requires an average capital investment of approximately $590,000. The estimated ownership and operating cost of using one harvest unit at capacity is $580,000 per year.

[f] A grid search procedure incremented the price of ethanol to determine the price level at which net present worth is equal to zero.

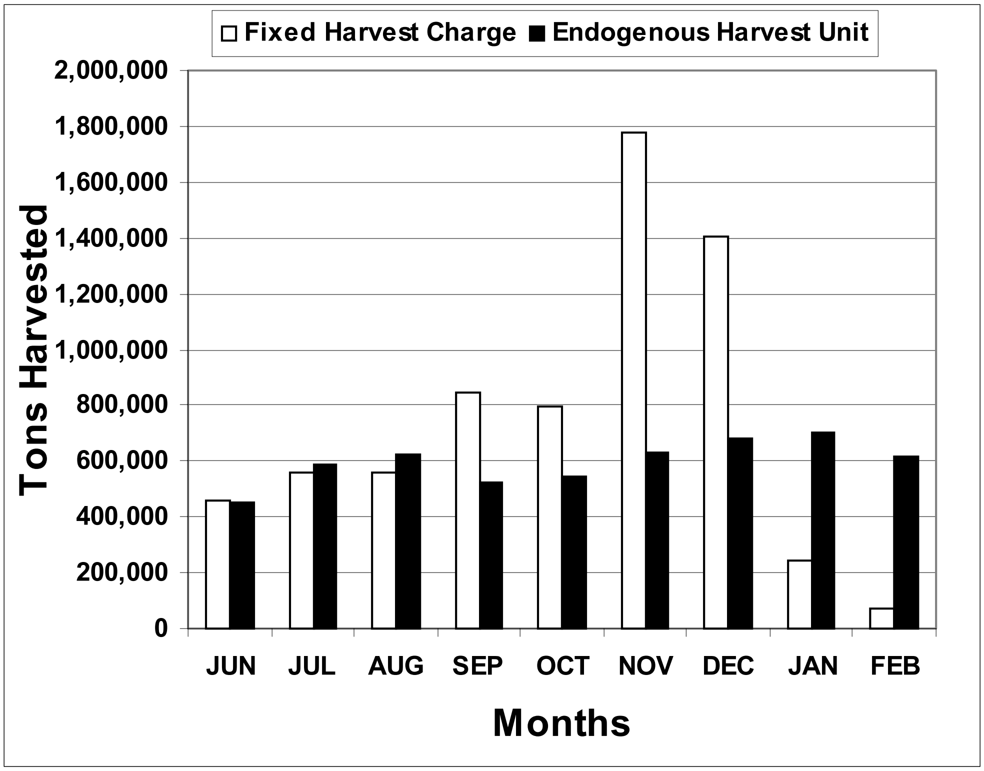

Figure 1. Total LCB Harvested by Month for both the Fixed Harvest Cost per Ton and the Endogenous Harvest Unit Models

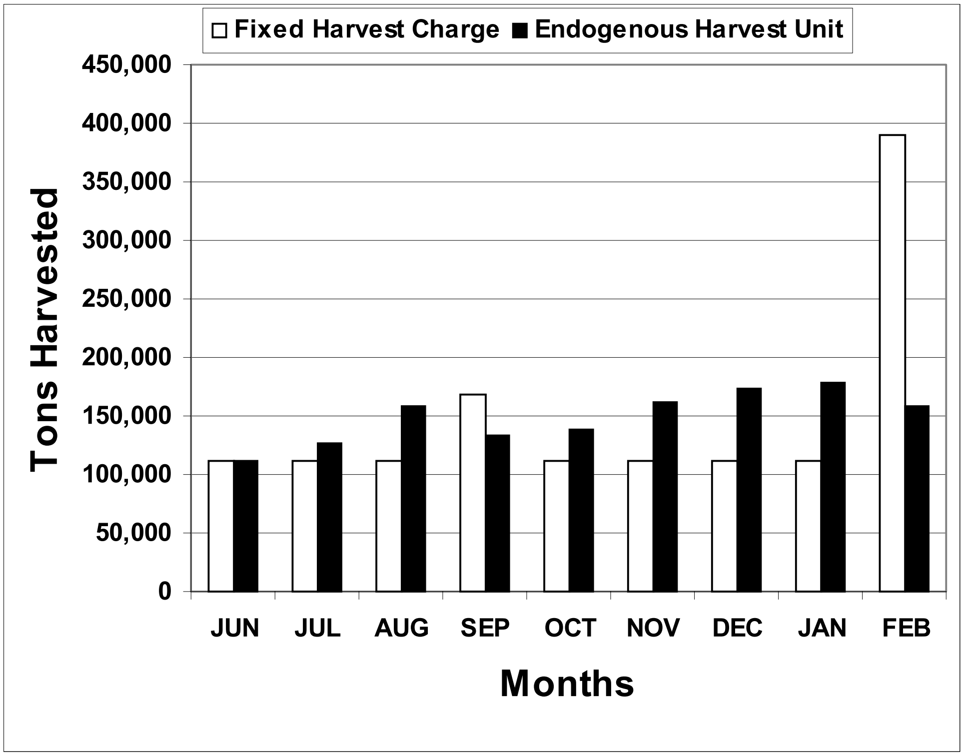

Figure 2. Total LCB Harvested by Month for the Breakeven Scenarios for both the Fixed Harvest Cost per Ton and the Endogenous Harvest Unit Models