# COST TO DELIVER LIGNOCELLULOSIC BIOMASS TO A BIOREFINERY

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|---|---|
| *Main Sets* | |
| $M$ | Month: $m$ = {Mar, Apr, May, Jun, Jul, Aug, Sep, Oct, Nov, Dec, Jan, Feb} |
| $J$ | Set of prospective plant locations: $j$ = {Canadian, Comanche, Custer, Garfield, Jackson, Okmulgee, Payne, Pontotoc, Texas, Washington, Woodward} |
| $S$ | Set of plant sizes: $s$ = {Small, Medium, Large} |
| $G$ | Vector of products (e.g. ethanol and other) and by-products (e.g. $CO_2$, $N_2$, and Ash) |
| $I$ | Set of biomass supply centers (or source counties): $i$ = {All counties in Oklahoma, Panhandle counties in Texas and counties in southern Kansas} |
| $K$ | Set of feedstock species: $k$ = {Corn stover, Wheat straw, Old world bluestem, Tall fescue, Bermudagrass, Native tall, Native medium, Native short, Switchgrass} |
| $F$ | Level of nitrogen application (in lbs/acre): $f$ = {0, 50, 100, 150, 200} |
| $Ft$ | Set of facilities. In this case, $ft$ = {Processing facility, Storage facility} |
| $L$ | Land Categories: $l$ = {Cropland, Improved pasture, Pastureland, CRP} |
| *Subsets* | |
| $b(g)$ | Set of process byproducts or externalities: $b$ = {e.g. $CO_2$, $N_2$, Ash} |
| $cr(k)$ | Set of crop residues: $cr$ = {Wheat straw, Corn stover} |
| $e(g)$ | Set of process main products(s): $e$ = {Bioproduct e.g. ethanol} |

| PARAMETER | DESCRIPTION |
|---|---|
| $\rho_g$ | Price per unit of output *g*, may be positive for biorefinery outputs such as ethanol or a positive externality, or negative for negative externality or output with disposal cost. |
| $\alpha_k$ | Cost of producing a ton of biomass type *k* |
| $\gamma_k$ | Cost of storing a ton of biomass *k* in the field |
| $\tau_{ij}$ | Round-trip cost of transporting a ton of biomass from source county *i* to plant location *j* |
| $\psi_k$ | Cost of procuring a ton of biomass of species *k* |
| $\Omega$ | Annual cost of a harvest unit |
| K | Cost of harvesting a ton biomass |
| $\theta_{ik}$ | Proportion of biomass *k* stored in county *i* that is usable a month later |
| $\phi_{jk}$ | Proportion of biomass *k* stored at plant *j* that is usable a month later |
| $\lambda_{kg}$ | Quantity of output *g* produced from a ton of biomass *k* at the plant |
| $\lambda_{ke}$ | Quantity of ethanol (*e*) produced from a ton of biomass *k* at the plant |
| $LAND_{ik}$ | Total acres of land producing biomass *k* in county *i* (acres) |
| $BP_{ikl}$ | Proportion of land of category *l* in county *i* with biomass *k* available for harvesting for biorefinery use |
| $YAD_{km}$ | Yield adjustment factor for biomass *k* if harvested in month *m* |
| $BYLD_{ikf}$ | Yield (tons/acre/year) of biomass *k* if under fertility regime *f* at county *i* |
| $TAFC_{sft}$ | Amortized fixed cost of constructing and operating facility *ft* of plant size *s* |
| $CAPHU_{im}$ | Capacity of a harvest unit in county *i* month *m* |
| $CAPP_s$ | Processing facility capacity associated with plant size *s* (gallons of ethanol per month) |
| $CAPS_k$ | Biomass storage facility capacity associated with plant size *s* (tons of biomass) |
| $MBINV_s$ | Minimum biomass inventory for plant size *s* (tons/month) |
| $PVAF$ | Present value of annuity factor, where the annuity factor is the annual net benefit for the ethanol production industry |
| $r$ | Market discount rate, used in the computation of $PVAF$ |
| $t$ | Plant useful life used in the computation of $PVAF$ |

| VARIABLE | DESCRIPTION |
|---|---|
| $NPW$ | Overall net present worth of the industry |
| $q_{jsgm}$ | Quantity of output *g* produced in month *m* by a plant of size *s* at location *j* |
| $A_{ikfm}$ | Acres of biomass *k* harvested at source *i* in month *m*, where *k* is under fertility regime *f* |
| $xsp_{ikm}$ | Tons of biomass *k* harvested in month *m* and stored in county *i* |
| $xt_{ijskm}$ | Tons of biomass *k* transported in month *m* from county *i* to a plant of size *s* at location *j* |
| $x_{ikfm}$ | Tons of biomass *k* harvested in month *m* at source *i*, where *k* is under fertility regime *f* |
| $xs_{ikm}$ | Tons of biomass *k* stored at source county *i* in month *m* |
| $xsn_{ikm}$ | Tons of biomass *k* removed from storage at source *i* in month *m* |
| $xhu_{im}$ | Proportion of a harvest unit used in county *i* in month *m* |
| $HU$ | Integer variable representing the total number of harvest units used |
| $xs_{jkm}$ | Tons of biomass *k* stored at plant location *j* in month *m* |
| $xp_{jskm}$ | Tons of biomass *k* processed by a plant of size *s* at plant location *j* in month *m* |
| $\beta_{js}$ | A binary variable associated with plant size *s* at location *j* |

# CHAPTER I

# INTRODUCTION

## Background Information

A biorefinery is a facility that converts (refines) biological material (biomass) into products (Kamm and Kamm). Breweries and wineries are examples of facilities that convert biological material (i.e. grain, grapes) into relatively high value products including beer and wine. A facility that produces subsidized ethanol from corn grain is another example of a biorefinery. In some respects, a biorefinery is similar to a petroleum refinery that uses crude oil as a feedstock and produces fuels and other products.

A crude oil refinery may produce a wide array of petroleum products including gasoline, diesel fuel, jet fuels, kerosene, heating oils, asphalt, and propane gas. Petrochemicals processed from crude oil are used to make many products including cosmetics, clothes, and plastics. Plastics made from crude oil are used in a wide variety of products.

Research programs to develop technology that will enable converting lignocellulosic biomass (LCB) feedstock into useful products are underway at government, university, and private facilities. The economic success of an unsubsidized

LCB biorefinery will depend upon its ability to either produce (a) unique valuable products or to produce (b) products more cheaply than fossil-based substitutes.

Experience from conventional crude oil refineries and electric power generating plants suggest that (a) the cost of delivered feedstock is a major component of the cost to produce products, and (b) size economies are very important in the production of bulk commodities. Some electric power generating plants that use coal as a feedstock require 110 100-ton railroad cars per day each day of the year. For example, a unit train of 110 cars delivers coal from mines located in Powder River Basin, Wyoming, to an electric power generating plant at Muskogee, Oklahoma, on a daily basis. The average delivered price of coal to electric utilities in the U.S. in 2002 was approximately $25 per ton (Department of Energy). The demand and use of fossil fuels, including coal and other liquid fuels, has been increasing.

Concerns about the effects of growing demand and use of enormous quantities of fossil fuels have triggered public policy debates to evaluate alternative sources of energy. Several authors have reported the adverse effects of heavy utilization of fossil fuels: (1) the U.S. dependence upon imported fossil fuels has important economic costs as evidenced by the oil price shock of the 1970s and 2004; (2) environmental degradation, including air pollution, global warming, and acid rain, phenomena that may have detrimental effects on natural habitat, wildlife and human beings; and (3) eventual depletion of fossil fuel reserves (Hohenstein and Wright; Wyman, 1994; Nienow et al.; Bhattacharya et al; Koh and Hoi; Sajjakulnukit and Verapong).

Fossil fuels are compounds of carbon and hydrogen. When completely combusted, fuels produce energy and byproducts such as $CO_2$ and water vapor that are released into the atmosphere. With no equal increase in the use of the atmospheric carbon dioxide, this results in a net increase in the amount of atmospheric carbon dioxide. In certain circumstances, combustion may be incomplete. Incomplete combustion produces carbon and partially oxidized carbon as CO (Carlin). Carlin reported that since air is 21 percent oxygen and 78 percent nitrogen, combustion of hydrocarbons in the presence of air results in nitrogen oxides (i.e. NO and $NO_2$ compounds) and sulfur dioxide ($SO_2$). Sulfur dioxide results from combination of sulfur contained in fossil fuels and oxygen from air. Accumulation of these gases in the atmosphere "blocks infrared radiation to outer space, and reradiate the captured heat to the atmosphere causing a global warming effect and, at the same time, polluting the fresh air" (Carlin, page xii). Furthermore, nitrogen oxides and sulfur dioxides in the air form nitric acids and sulfuric acids that combine with rain causing acid rain (Carlin; Sajjakulnukit and Verapong; Nienow et al.).

Consequently, interest in renewable energy development and use has considerably increased with ethanol being widely recognized as an acceptable substitute for gasoline or as an additive to gasoline. Biomass has long been used as a source of energy through direct combustion. Recent technology developments could make it possible to economically use LCB as a source of renewable energy. In contrast to use of fossil fuels, the use of renewable energy from LCB may add less net carbon to the atmosphere since some of the atmospheric carbon may be sequestrated into carbon compounds during the growth of the plants (Lynd et al.; Ranney and Mann). The quantity of carbon added to the atmosphere net of carbon sequestration depends upon the quantity of fossil fuels used to grow, harvest, and transport the LCB. Nienow, McNamara and Gillespie observed that utilizing biomass for energy production does not contribute any net carbon dioxide to the atmosphere since plants use carbon dioxide during their growth cycle. Furthermore, due to an expected increase in revenues, the use of biomass is expected to stimulate rural economies with increased crop revenues (Nienow, McNamara and Gillespie).

Renewable energy could be produced from any sugar or starch biomass crop. From 1993 to 2002 U.S. ethanol production almost doubled from 1.15 billion gallons to 2.13 billion gallons, and production in 2003 rose to more than 2.81 billion gallons (Renewable Fuels Association). Ethanol is largely (>95%) produced from cornstarch. But "the high cost of corn grain, 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 feedstock for ethanol production" (O'Brien et al., page 15) and production of other bioproducts. Epplin (1996) and Tembo contend that technology for ethanol-conversion could be most efficient with lignocellulosic plants such as grasses, crop residues and trees compared to corn grain. The primary problem of grain-to-ethanol production in the U.S. has been and still remains economic, as evidenced by the federal ethanol subsidy. Conversion technologies used in grain-based biorefineries are approaching their inherent theoretical limits. Alternative methods for producing biobased products including ethanol are being developed that are based upon the use of low value LCB such as crop residue and perennial grasses.

## Advantages of LCB Biorefinery System

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 biorefining technology is that a variety of feedstock, 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. While the data suggest that in the absence of subsidies or other government interventions, it would be very difficult for an LCB biorefinery to compete with a conventional crude oil refinery in the production of bulk commodities such as liquid fuels, it is possible that LCB may be used to produce unique valuable products. And, feedstock cost is expected to be an important component of total production costs.

Use of a variety of feedstock 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. The infrastructure for production, harvest, storage, transportation, and price risk management of corn grain is well developed. 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.

## The Problem Statement

Prior to Tembo, most models of LCB production, harvest, and transportation included a single point estimate of the harvest cost per ton or per acre. While this may be a reasonable approach if the feedstock is corn grain, it may be less so for a feedstock such as LCB for which a harvesting infrastructure does not exist. The ability to economically produce valuable bioproducts from low-cost LCB will be key to making these products economically competitive. It is, therefore, important to effectively capture the procurement, harvesting and transportation costs of LCB in the project appraisal of an LCB biorefinery system.

This research attempts to provide insight on the delivery cost of LCB feedstock to a biorefinery by properly accounting for cost of harvesting, storage and transportation. Previous studies on the economics of LCB biorefinery have not considered a coordinated set of harvest machines and harvest crew in their accounting for harvest cost. The hypothesis is that such studies may have underestimated the delivery cost of biomass to a biorefinery. Furthermore, studies that have assumed per unit harvest cost exogenous to the model may have failed to capture the true harvest cost and may not have taken advantage of economies of scale that come with a coordinated set of harvest machines.

## Objectives of the Study

The focus of the proposed research is to determine the cost to deliver a steady flow of LCB feedstock throughout the year to a biorefinery optimally located in Oklahoma.

Specific objectives include:

1. To determine how the method of modeling harvest and procurement cost changes the cost to deliver a ton of LCB (from crop residue, indigenous native prairies, improved pastures, Conservation Reserve Program (CRP) land, dedicated

switchgrass) to a biorefinery that can process 1,000, 2,000, or 4,000 dry tons of biomass per day.

2. To determine the cost to deliver a ton of crop residue (wheat straw and corn stover) to a 1,000, 2,000, or 4,000 dry tons of biomass per day biorefinery.
3. To determine the cost to deliver a ton of LCB from CRP land to a biorefinery, optimally located in Oklahoma, which can process either 1,000 or 2,000, or 4,000 dry tons per day.

# CHAPTER II

# LITERATURE REVIEW

## Chapter Outline

The purpose of this review is to highlight some of the important aspects of a viable LCB biorefinery industry. This review is divided into seven sections. The review begins by taking an account of feedstock resources available in the U.S. and the state of Oklahoma. It gives a brief and comprehensive report on the species and quantifies the acreage of biomass available for biorefinery processing. The second section considers documentation on potential bio-products obtained from processing LCB. It is anticipated that a wide array of bio-products could be produced from refining of LCB, similar to those obtained from petroleum refining. The third section attempts to comprehensively review the methods of determining LCB harvesting cost, transportation cost and total delivery cost in the economic analysis of a biorefinery. The few pieces reviewed have assumed harvest cost either as a parameter (i.e. as an exogenous cost per unit) or have incorporated some form of custom harvesting.

The fourth section of the review considers literature that has investigated the CRP as an opportunity for intensive production of biorefinery feedstock for bioproducts production. Section five reviews the economics of using crop residues as a sole LCB feedstock. Emphasis is geared towards resource availability for bioproducts production, adverse consequences of harvesting crop residues from the field and the delivery cost per ton. The review also considers the proportion of crop residues that can be removed from cropland without causing significant soil and fertility loss. Section five ends with an account that gives reasonable monetary values for harvested crop residues. Section six gives a brief account of the input/output energy balance ratio. The pieces reviewed have attempted to account for the energy balance for grain-to-ethanol and biomass-to-ethanol biorefinery processes. The review ends by summarizing the overall contributions of the various articles reviewed and then sets a stage for this paper's research.

## Feedstock Resources

LCB includes agricultural residues (e.g. corn stover, crop straw, sugarcane bagasse), herbaceous crops (e.g. alfalfa, switchgrass and perennial grasses), forestry residues and other woody biomass, wastepaper, urban wastes and other wastes (Wyman, 1994 and 1996; Hertzmark et al.). Tembo, Epplin, and Huhnke, noted that the state of Oklahoma has a variety of potential LCB feedstock, including plant residues, indigenous native prairies, and improved pastures. In addition, cropland could be used to produce dedicated feedstock crops such as switchgrass. Oklahoma has 15.6 million acres that are in native prairie grass, 4.9 million acres in improved pasture, one million acres in the federal government's CRP, and 7.7 million acres of harvested cropland. Crop residues are remains after harvesting grain and are readily found on cropland. On the other hand, native prairie grasses and improved pastures could be harvested from pastureland, rangeland and also on cropland. Some species of improved pastures and native prairies could be harvested from the CRP land.

Gallagher et al. reported the supply potential of crop residues in the U.S. Table 1 summarizes the aggregated regional biomass feedstock supplies of crop residues for the United States. The column of net residue production has been adjusted to enable retention of sufficient surface residue to limit soil erosion. The column for feed use indicates feedstuff demand for livestock feed. The column labeled industry supply refers to unused crop residues that would be available to a biomass processing industry.

**Table 1. Biomass from Crop Residues: Supply and Capacity for 1997 Baseline**

| Region | Net Residue Production | Feed Used | Industry Supply |
|---|---|---|---|
| | million lbs. | | |
| Corn Belt | 207,199 | 23,786 | 197,844 |
| Great Plains | 81,040 | 9,994 | 71,042 |
| West Coast | 7,377 | 2,573 | 4,805 |
| Delta (Rice) | 10,435 | 1,168 | 9,246 |
| Southeast (Sugar Bagasse) | 7,114 | 0 | 7,114 |
| Total | 313,165 | 37,521 | 290,051 |

Source: Gallagher et al.

Gallagher et al. also reported that potential for growth in the supply of crop residues exists because of crop yield growth and declining livestock demand for forage. They stated that if crop yields continue to grow at 56% like in the past two decades there would be 170 billion lbs more crop residues available. They also stated that the current 10% trend of declining cattle populations from the last two decades could account for another 75 billion lbs of crop residues in another two decades.

## Lignocellulosic Biomass Products

The process of bio-refining lignocellulosic biomass may produce a wide array of bio-products including ethanol, methanol, biodiesel, furfural, citric acids, acetic acid, carboxylic acids and other acids, ethyl acetate, bio-oils, polymers, oxygenated chemicals such as phenols and other chemicals (Ikram-ul et al.; Christen et al.; Gercel; Amen-Chen, Pakdel and Roy; Bouchard et al.; Meier and Faix; Schutt et al.; Skog and Rosen; Chen and Hsu). Skog and Rosen found that similar chemical products as those produced from petroleum refineries could be produced from biomass. These products include acetic acid, activated carbon, microcrystalline cellulose, dimethysulfide, ethanol, lignosulfonate, and methanol. They reported other chemicals derived from biomass that included polymeric adhesives, olefins, aromatic chemicals and some specialized chemicals. Some biorefinery chemicals processed from lignocellulosic biomass could be used to make many products including plastics. Meier and Faix reported that chemical compounds from lignocellulosic biomass processing are utilized as additives for flue gas cleaning of coal combustion, acetic acid for chip production, adhesives, fuel enhancers, specialty chemicals, and fertilizers.

McAloon et al. reported that cell matter, furfural, and acetic acid are potential co-products of biorefining of lignocellulosic biomass. They observed that markets for furfural and acetic acid were in place but they felt that the markets were not well established to sustain a fully commercialized lignocellulosic biorefining industry. Lignocellulosic biomass may also be used to produce industrial products. Lindstrom noted the recent suggestions for off-farm use of crop residues as raw materials for energy production and/or other manufactured products such as particle boards. Flaim reported that besides energy production, crop residues may also be used to manufacture industrial chemicals. He, however, noted the importance of crop residues as feed for livestock and their importance in environmental protection by reducing soil loss and enhancing soil fertility. Developing high-value bio-products from LCB biorefinery processing is a big challenge to a successful biomass industry. Besides these challenges, for the biomass processing industry to be economically feasible, achievement of a low biomass delivery cost is of paramount importance.

## Biomass Delivery Cost

Ultimately, the economic viability of a LCB biorefinery will depend in part upon the cost to produce, harvest, and deliver the LCB to a conversion facility. Harvest and transportation costs of LCB are important components of the cost of LCB biorefinery processing. English, Short and Heady found that the farm level costs plus transportation costs of crop residues for processing plants with capacity ranging from 24,800 to 297,600 tons per year ranged from 50% to 80% of the total cost, respectively. Farm level costs included harvesting costs, agronomic costs, as well as on-farm storage costs. In their analysis, agronomic costs included the opportunity costs of using crop residues for electric generation. The opportunity costs included the fertilizer value, and costs attributed to soil erosion and loss of humus. But the authors did not explain the factors considered in determining the cost of harvesting. They, however, used a harvesting system that harvested large stacks. They assumed that the stack could be left on the roadside with no cover without deteriorating.

Cundiff and Harris assumed custom harvesting in their estimate of delivery cost of LCB to a bioconversion plant. They found that harvesting and transportation costs comprised 69% of the total delivery cost of biomass to a conversion plant. Harvesting cost alone constituted 46% of total delivery cost. They reported a harvesting cost of $25/dry ton, transportation cost of $12.50/dry ton and total delivery cost of $54/dry ton. The cost they assumed for custom harvest rates was based on the 1995 prices for a range of sizes of large round bales. But in their article they did not explain whether the effects of weather changes were considered in determining days available for harvesting and hence harvest cost. Similar results have been reported in other studies that have assumed custom harvesting.

In their comparison of custom harvesting and transportation cost when biomass is handled as hay versus silage, Worley and Cundiff estimated the production, harvest, storage and transportation costs and found that harvest cost of hay alone was 48% of the total cost of all items considered. They reported a harvesting cost of $25/dry ton, transportation cost of $10.44/dry ton and total delivery cost of $52/dry ton. The harvest cost was obtained by analyzing the cost of operating a harvesting unit for 100 harvest days during a five month harvest season. All costs including the harvest cost were adjusted upwards (multiplied) by a factor of 1.15 to account for increased costs due to weather delays. By assuming custom harvesting their harvest costs were much higher than if they had endogenously determined the number of harvest machines and harvest cost.

Assuming a custom harvesting system, Cundiff simulated harvest cost by using five different large-round-bale harvesting systems for biomass. The biomass used in his study was switchgrass and he assumed that cutting was done by a mower-conditioner, raking by a rake-tedder and baled with a large round baler. The five systems assumed three different baler sizes: 1.8m x 1.5m, 1.8m x 1.2m, and 1.5m x 1.2m, each representing the diameter and the width of the bale. The two additional systems used were obtained by varying the 1.8 x 1.5 system. The total harvest costs were approximately equal for the 1.8 x 1.5 and 1.8 x 1.2 systems, $15.70/ton and $15.61/ton, respectively. He also found that an increase in harvest days reduced the per ton harvest costs by 10%. Only in-field costs were computed, therefore the simulated costs were lower than commercial practices. Since the simulated results of harvesting and transportation costs reported by Cundiff were not complete he reported that they should not be directly compared to custom harvest rates. The simulation was intended to provide a comparison between the five systems in an ideal harvesting situation. Cundiff stated that "the production of herbaceous biomass as a feedstock for bioconversion is an equipment-based enterprise, meaning that, above some yield threshold, harvest/handling/hauling equipment productivity has more impact on delivered cost than land productivity" (Cundiff, page 77).

Cundiff and Marsh surveyed a number of studies on custom harvesting. The overall mean for all surveyed data suggested a harvest cost of $28.22/ton for square bales, and $28.09/ton for round bales. In their study, they simulated harvest and storage costs for bales of switchgrass in the Southeastern United States. They found that harvest cost was $11.65/ton for square bales and was $15.16/ton for round bales. They noted that their simulated results were far much lower than most other studies had suggested as the cost of harvesting biomass. They reported that the simulated results did not include overhead costs as did the custom harvest rates.

Epplin (1996) considered a coordinated harvest system like that of custom harvesting and found that the annual stand maintenance and harvesting cost were 32% of the cost to deliver one dry ton of switchgrass biomass to a conversion facility. He assumed that machinery and equipment that would be used for harvesting and transportation would be owned by either the plant facility, a cooperative, or by specialized firms, but not by the land owner. He envisioned harvest crews that are managed from a central location, equipped with specialized equipment that could harvest for an extended period. In order to provide a steady flow of biomass to the plant facility, he envisioned that transportation crews could work throughout the year. He stated that "an economically efficient biorefinery system would require coordination of production and transportation with processing" (Epplin, page 460). In his study, he considered switchgrass as the sole feedstock for a biorefinery plant facility located in the Southern Plains of United States. In his estimation of harvest cost he did not consider the effects of weather on the harvest days and, hence, on the harvest cost. He reported a harvesting cost of $10.81/dry ton, transportation cost of $10.71/dry ton and total delivery cost of $33.66/dry ton. He observed that his reported delivery cost of biomass (switchgrass) was lower than the costs reported by other studies because (i) his machinery cost was spread over a vast number of acres resulting in economies of size; and (ii) as for harvesting, he assumed a harvesting system managed and owned by the plant not custom harvesting that are generally higher. His reported estimates were based on switchgrass yields of 4 dry tons/acre.

Sokhansanj and Turhollow developed baseline costs for collecting, baling, and transporting corn stover by using round and rectangular baling systems. They selected two systems for collecting corn stover residue as bales. One system consisted of a combination of shredding-windrowing operations followed by round baling. The other system consisted of separate shredding and windrowing (raking) operations followed by large rectangular baling. An average distance between the farm and storage of 5 miles was assumed. Their calculated feedstock cost included costs for collecting, baling, and transporting corn stover to a covered storage. They reported feedstock cost of \$19.70/dry ton and \$21.40/dry ton for the round baling system and for the rectangular baling system, respectively. The cost included wages but did not include any additional payment to the farmer. Transportation cost was \$5.56/ton and \$7.80/ton for the round bale and rectangular bale systems, respectively. Harvesting cost was \$14.14/ton and \$13.60/ton for the round bale and rectangular bale systems, respectively. They noted that reducing the cost to deliver a ton of feedstock was key to reducing the overall cost associated with biomass conversion.

Gallagher et al. estimated the supply cost and social costs for harvesting crop residues in the United States. They developed a general harvest cost function. They assumed that costs may vary on a per acre basis or on a per output basis. They approximated direct harvest costs by replacement and operating costs for harvesting machinery. They assumed harvesting hay in large round bales. These cost estimates included chopping, baling, and on-farm transportation. The operating expenses included labor costs. The costs for chopping and baling were estimated on a per acre basis while farm haul costs were estimated on a per-ton basis. Included in the harvest cost were the cost of moving the bales to a convenient site for on-farm storage and indirect fertilizer costs of utilizing crop residues for alternative uses such as biorefinery processing. Considering all the crop residues they used in their study, the average harvesting cost was \$18.23/ton, and, considering an ethanol plant, the transportation cost was \$3.39/ton.

Ho (1985b) noted that considerable amounts of crop residues could be harvested without causing soil erosion problems if proper agronomic and engineering practices were rightly followed. He reported that the quantity of crop residues that could be economically harvested were affected by the geographical distribution of the areas where crops were grown and the rotation of crops practiced. He observed that the method of biomass harvesting, transportation to the central facility, alternative uses of crop residues and the cost of implementing soil erosion control affect the economics of harvesting crop residues. Ho was studying the production of methane via dry fermentation route with particular consideration to the cost of harvesting and transporting the feedstock to a central processing plant.

To estimate biomass production he assumed a ratio of 1:1 between residue weight and grain weight. Both weights were assumed on oven-dry basis. He reported higher ratios for straw to grain of 1.7 for wheat and 2.0 for oats. He assumed that a collection efficiency of 75% could be achieved using existing harvesting machinery. Two major scenarios were considered: one was the collection of residue by farmers using existing machinery and the other was using equipment owned and operated by a central facility. Harvesting costs using farmers' equipment ranged from \$7.40/ton to \$9.80/ton and harvesting cost by a central facility was \$7.50/ton. His harvesting costs were not endogenously determined. He assumed a particular harvesting system with a certain number of machines and determined the harvest cost per ton, which was included in his analysis as a parameter. He reported that custom harvesting costs were over 50% higher than machinery operating costs. He wrote that custom harvesting costs are generally higher because they reflect the management cost and profit of the custom operator. He assumed that harvesting would be carried out over 25 days due to weather, but did not explain how he determined these estimated days.

Some studies have assumed harvest cost as a parameter (i.e. as a fixed cost per unit). English et al. conducted an economic feasibility of using crop residues to generate electricity in Iowa. They assumed harvest cost of $7.27/ton. This was obtained by averaging reported harvest costs from a number of studies they reviewed. The reviewed studies assumed a six-ton stack harvester that had an annual output of 1,000 tons. They defined the different costs used as either direct or indirect. In their definition, direct costs included costs associated with harvesting, transporting, and processing the crop residues and the agronomic costs of nutrients replacement. The indirect costs were those attributed to cropping pattern shifts by farmers.

Kaylen et al. studied the economic feasibility of producing ethanol from lignocellulosic biomass feedstock in the state of Missouri. The feedstock considered included crop residues, woody biomass, and dedicated energy crops. They assumed a per unit feedstock cost of $25 per ton for crop residues and woody biomass. This price included chopping, raking and baling of residues (i.e. harvesting cost), but did not include transportation cost to the plant. For dedicated energy crops the feedstock cost was assumed to be $43.75 per ton. They reported that feedstock (primarily crop residues) cost were 21% of the total annual plant costs (excluding capital cost). By using a fixed cost per unit the study might have not used a correct estimate for harvesting cost. They did not consider a coordinated harvest unit with specialized harvest crew and machinery. It is very unlikely their harvest costs considered the effects of weather changes on available harvest days, and, hence on the harvest costs. In their base case scenario, crop residues were preferred over woody biomass because of the higher content of hemi-cellulose and the significantly lower level of lignin. They reported that hemi-cellulose is used to produce furfural, which is a more valuable product than ethanol. Dedicated energy crops were not used in the optimum solution primarily because they were more expensive (over $43/ton) than was assumed for both crop residues and woody biomass, each at $25/ton. They found that co-production of ethanol and furfural appeared to be quite profitable. They reported that a biomass biorefinery may be developed that could produce a variety of valuable products depending on market demand, price, and other factors.

Tembo, Epplin and Huhnke, in their study in which they used a fixed harvest cost per acre, reported that harvest costs constituted 8% of the total cost to produce a gallon of ethanol. In their analysis, though they used a coordinated system of harvest machines to determine the fixed harvest cost used, less attention was paid to the complexities of harvesting such as available harvest days in a month and coordinated set of machinery that would result in the lowest cost at intensive levels of use. Furthermore, because of their assumption of harvest cost per acre in their study, harvest costs of the same species varied per ton across regions.

A coordinated harvest system that includes labor hours operated by a commercial company or developing in concert with a LCB feedstock biorefinery industry is anticipated to be more efficient than harvesting done by individual farmers. This is because harvest windows differ across species enabling the use of harvest and collection machinery throughout many months and over large acres reducing the fixed costs of harvest machinery per unit of feedstock. Thorsell et al. found that such a coordinated harvest system with adjusted implement speed to maintain a relatively constant LCB harvest capacity per hour, generated harvest costs ranging from \$12.70 to \$9.98 per ton for yields ranging from 1.0 to 6.0 ton per acre. They reported that these estimates were lower than previous estimates in other studies (Schechinger; Sokhansanj and Wright).

The assumption of a coordinated set of harvesting machines may give a better estimate of harvesting cost than the use of a fixed cost of harvesting per ton or acre. Based on the literature reviewed in this section, this study assumes the endogenously determined harvest unit as developed by Thorsell. As Epplin (1996) suggested, the harvest units may be controlled at the central facility. Another important aspect is that the capacity of each harvest unit is affected by the available days for harvesting, which are, themselves, based on historical weather patterns for that particular locality, in this case a county. Table 2 summarizes the contributions of various studies that were reviewed on the delivery cost of LCB biomass as a feedstock for biorefinery processing. The various categories of costs are all in U.S. dollars per dry ton of biomass.

## Potential for Use of CRP Acres to Produce Biorefinery Feedstock

The Conservation Reserve Program (CRP) was established by enabling legislation in the 1985 Farm Bill (Martin et al.; Swanson, Scott and Risley; Sullivan et al.). It sets aside highly erodible and environmentally sensitive acres of cropland under 10-15 year contracts. Land under CRP is planted to conservation crops such as perennial grasses and

**Table 2. Cost Categories of LCB Feedstock Reported by a Variety of Studies**

| | | Cost Categories $/Dry Ton | | | | | |
|---|---|---|---|---|---|---|---|
| Source | Feedstock | Production Cost | Acquisition Cost | Harvest Cost | Storage Cost | Transportation Cost | Total Cost |
| Cundiff | Switchgrass | | | 15.70 | | | 15.70 |
| Cundiff and Harris | Switchgrass | 16.50 | | 25.00 | | 12.50 | 54.00 |
| Cundiff and Marsh (Square Bales) | Switchgrass | | | 15.16 | 2.91 | | 18.07 |
| Epplin (1996) | Switchgrass | 12.14 | | 10.81 | | 10.71 | 33.66 |
| English et al. | Crop residue | | 9.38 | 7.27 | | | 16.65 |
| English, Short and Heady (Plant capacity of 297,600) | Crop residue | | 4.22 | 7.46 | | 1.11 | 12.79 |
| Gallagher et al. | Crop residue | | | 18.23 | | 3.39 | 21.62 |
| Ho (1985b) | Crop residue | | 7.50 | 7.50 | | | 15.00 |
| Kaylen et al. | Crop residue | | | 25.00 | | | |
| | Energy crops | | | 43.75 | | | |
| Sokhansanj and Turhollow | | | | | | | |
| Round bales | Corn stover | | | 14.14 | | 5.56 | 19.70 |
| Rectangular bales | Corn stover | | | 13.60 | | 7.80 | 21.40 |
| Tembo, Epplin and Huhnke | Variety | 15.00 | | 5.25 | 6.00 | 12.00 | 38.25 |
| Thorsell et al. | Variety (Yield 5 ton/acre) | | | 10.22 | | | |
| Worley and Cundiff | Crop residue | 16.52 | | 25.00 | | 10.44 | 52.00 |

trees, and landowners receive an annual rental payment for the land from the federal government on per acre basis. The purpose of CRP is to cost-effectively assist producers in conserving and improving soil, water, and wildlife resources (Sullivan et al.; Office of the Federal Register). Epplin (1996) reports that between 1986 and 1989 more than 988,000 acres of Oklahoma cropland were under CRP for an average annual payment of $42.11 per acre.

The 1985 Farm Bill generally provided that no commercial use could be made of land enrolled in CRP, but permitted haying or grazing during droughts or similar weather-related emergencies. This issue of inability to unconditionally use the LCB resources available on CRP land has been debated since the onset of the program. Several authors have suggested using land under CRP for production of LCB feedstock for biorefinery use and have considered the economic gains to both farmers and the federal government from using CRP land for LCB production (Downing, Walsh, and McLaughlin; Walsh, Becker and Graham; Epplin (1996); Walsh et al.).

Goodman, Coady and English conducted a study to examine biomass energy crop production on highly erodible cropland in terms of farm profitability, erosion control, and level of government involvement. They stated that besides erosion control and farm profits, the development of alternative renewable energy resources was another important policy issue. They reported that by using highly erodible cropland to produce biomass energy crop, farmers may achieve both a high level of erosion control and an acceptable level of profitability. Even after grass has been harvested, soil erosion may be controlled by grass stubble and stumps that remain after energy crops are harvested. The grass stumps may also grow into replacement crops. They reported a significant reduction in erosion due to production of switchgrass on highly erodible cropland enrolled in the CRP. In their results they found that costs of government programs targeting erosion control could be reduced by allowing harvest of biomass produced on highly erodible cropland which is currently enrolled in the CRP.

The CRP could mitigate some of the problems associated with excess crop production and protect erodible cropland from serious soil erosion (Martin et al.). Nevertheless, the CRP may have noticeable impact on agricultural prices and incomes for farmers who continue to produce grain and may have deleterious effects on the rural America (Hyberg, Dicks and Hebert; Martin et al.). Martin et al. reported that farming areas with comparatively productive land notwithstanding highly erosion prone could doubtlessly be adversely affected by the CRP. Furthermore, they observed that the reversal of many county economies from a production-oriented to a transfer payment-oriented economy resulted in noticeable economic shock. They concluded that the CRP could be a conflict between the economic objectives of the local county or community and those of the nation and sectoral policy. They observed that the CRP resulted into potential conflict between broad agriculture policy and rural development policies, strategies, and programs. They noted that despite rental payments that were made to landowners for their retired cropland, implementation of CRP reduced agricultural production enough to cause economic activity to decline. They suggested using the land enrolled in CRP for production of biomass energy crops like switchgrass.

Walsh, Becker and Graham reported that despite its effectiveness at maintaining environmental quality, the CRP was also expensive (costing the federal government approximately $1.8 billion annually as of 1995). In its 1995 Farm Bill sitting, Congress examined several ways to reduce the cost of the program to the federal government, among which was the potential to produce and harvest LCB feedstock in exchange for reduced rental rate. Walsh, Becker and Graham noted that the CRP rental payments by the federal government could serve as a de facto subsidy for the production of LCB feedstock and reduce the price of these crops. In their study, Walsh, Becker and Graham considered switchgrass and short-rotation woody crops (i.e. hybrid poplar and hybrid willow). Two options were used to model the potential price reduction, hence subsidy, in the biomass energy crop: (a) in the first option they assumed a program similar to deficiency payments with an established rental rate and where the government only pays the difference between the profits earned from LCB and the prevailing rental rate; (b) in the second option they assumed a predetermined percent reduction in the rental payments of producers whose combined income from LCB profits and the reduced rental payment exceed the nonreduced rental payment.

Walsh, Becker and Graham noted that due to the subsidy the market price of biorefinery feedstock could lower and hence improve economic competitiveness of LCB relative to fossil fuels. Walsh et al. reported that as a result of LCB feedstock production for bioenergy on CRP land, farm income would be expected to increase by nearly $6 billion leading into a win-win situation. But not all CRP land could be used for LCB feedstock production; lands that are considered environmentally sensitive would be restricted from LCB feedstock production by USDA (Walsh et al.). It should be noted that farmers would only participate in LCB feedstock production if the price paid for the crop plus the reduced total rentals received are at least equal to the existing CRP total rental payments for the land.

The advice by Walsh et al. and other writers on the possible commercial use of CRP lands were followed in the formulation of the 2002 farm bill. The 2002 farm bill enables managed haying, grazing, and biomass harvest on CRP land a maximum of one in every three years (Office of the Federal Register). With current regulations it is likely that removal of biomass from CRP land in Oklahoma could be conducted over a 60-day period beginning July 2. The amendments included in the 2002 Farm Bill that provide for managed harvesting and grazing, including the managed harvesting of biomass allow for production and harvesting of LCB for biorefinery feedstock.

Total CRP enrollment in the United States in 2003, was 34.2 million acres at an annual rental rate of $47.72 per acre. This included more than one million acres in the state of Oklahoma at an average rental rate of $32.45 per acre (USDA). This large acreage of perennial grasses could serve as a resource for providing biorefinery feedstock. The 2002 farm bill requires that acres used for managed grazing, haying or biomass harvesting be assessed a 25% annual rental payment reduction. This could reduce the total federal government’s annual CRP rental payment. To date, no study has been conducted to investigate the feasibility of a biorefinery in Oklahoma that includes purchase, harvest, storage, transportation, and processing costs of biomass feedstock grown exclusively on CRP land.

Besides the CRP land, LCB feedstock could be harvested on cropland. The following section reviews literature that has investigated crop residues as potential feedstock for biorefinery processing. Several issues pose big challenges for using crop residues as feedstock for biorefinery processing.

## Crop Residues as Potential LCB Feedstock

Crop residues are used on the farm for feed and bedding. But, most are left in the field after harvest. Off-farm use of crop residues as raw material for production of energy and/or other manufactured products has been suggested (Lindstrom). Lindstrom observed that it was commonly assumed that crop residues are a waste product and have no value when left on the land. Several authors have reported that crop residues can serve as a major low-cost feedstock for biorefinery production (English, Short and Heady; Gallagher and Johnson; Kaylen et al.; Kadam and McMillan; Tembo, Epplin, and Huhnke; Kim and Dale). In their study on generating electricity using crop residue, English, Short and Heady concluded that the rapid upward trend in energy prices could make crop residues feasible for energy production. Currently, crop residues are not used for biorefinery production in commercial quantities. Wyman (1996) reported that more than 90% of corn stover in the United States was left in the fields.

According to the 2002 census of agriculture, 434.2 million acres of 938.3 million acres in farms were under crop production. In Oklahoma, out of 33.6 million acres of farmland, 14.8 million acres were under crop production including pasture. A major byproduct of this extensive cropping is crop residues, which are believed to be an excellent feedstock for biorefinery processing due to their high content of hemi-cellulose and cellulose (Kaylen et al.).

Kadam, Forrest and Jacobson reported that less than 5% of corn stover was physically collected for off-field use. Kadam and McMillan observed that among the various LCB resources available, agricultural residues exist in large quantities. In the U.S., crop residues could be a major potential biorefinery feedstock responsible for a major proportion of the total potential bioproduct production (Kim and Dale). Kadam and McMillan observed that corn stover was the dominant feedstock in the U.S., representing 80% of the total agricultural residues and was concentrated in the Midwestern region of the United States.

In the state of Oklahoma wheat dominates other crops in terms of production. For the period between 1997 and 2001, Kadam and McMillan estimated that an average of 4.3 million tons of wheat per year was produced in Oklahoma with a total wheat straw production of 5.7 million dry tons per year. They found that it was sustainable to harvest 2.3 million dry tons per year of wheat straw. With a total production of 33 million dry tons/year of wheat straw in the U.S. during the same period, Kadam and McMillan estimated that 2.5 billion gallons of ethanol per year could be produced assuming a straw-ethanol conversion rate of 70 gallons per dry ton.

## Importance of Crop Residues in the Field

The value of crop residues for fertility maintenance, erosion control and improvement of soil structure has been well documented. It may be unacceptable to harvest large quantities of crop residues since crop residues have an important role in maintaining soil organic matter content, soil physical and chemical properties, controlling both wind and water erosion and conserving moisture. Flaim reported that crop residues contribute to soil fertility maintenance through enhanced water percolation, recycling minerals and nutrients, decreased evaporation losses, and increased decomposition and soil aeration. Flaim stated that biological activities enhance soil formation through physical and chemical weathering, which in turn replenishes nutrients lost by residue removal.

Lindstrom conducted a study on natural runoff plots to determine the effect of tillage management systems and levels of crop residue harvesting on water runoff, soil erosion and nutrient removal from reduced tillage and no-till cropping systems. For both tillage management systems (i.e. reduced tillage and no-till cropping systems) he observed that harvesting crop residues increased water runoff resulting in increased soil erosion. He reported that harvesting residues at high rates resulted in considerable loss in soil nutrients. He noted that if large quantities of crop residues were removed from land, nutrient supplement from inorganic fertilizers could not adequately add the lost nutrients.

In their study, Pimentel and Krummel observed that the current levels of soil erosion on U.S. croplands make harvesting of crop residues unacceptable since it only intensifies the U.S. land degradation problem. They found that in addition to land degradation and based on average corn yields, harvesting corn stover was unprofitable. However, they reported that producing LCB for energy could effectively control erosion if the crop stand was dense and well maintained as perennial planting. They observed that production of LCB energy crops protected surface water quality. Though their cost accounting estimates showed the system to be unprofitable, they reported that an increase in future energy prices would make this system profitable.

## **How Much Residues Can Be Safely Harvested?**

Although a certain quantity of residue is required to protect the soil from erosion, some residue can be safely removed. Use of crop residues may not pose a big threat, especially, if a small proportion of crop residues were removed for off-farm use. Some authors have indicated that harvesting crop residues for biorefinery processing could not increase soil erosion or lead to loss of soil fertility.

In a study of how much crop residues could be safely harvested, Ho (1985a) reported that considering the current farming activities, harvesting crop residues could cause soil erosion. He noted that the loss of top soil could result in long-term loss in soil productivity coupled by sedimentation of streams and rivers. Since soil erosion is affected by climate, soil type and topography, Ho stated that harvesting of crop residues should be considered on a regional basis. The economic viability of using crop residues as feedstock for biorefinery processing depends on the sustainable flow of the feedstock in adequate amounts. Ho stated that the quantity of crop residues that could be safely harvested is important in relation to economics of residue collection and transportation. Ho also stated that if, due to the need of controlling soil erosion, only a small proportion of crop residues could be harvested, the economic viability of a biorefinery that utilizes crop residue could be adversely affected.

Since crop residues are scattered in the fields their harvesting and collection constitutes a major cost item of the total delivery cost. Furthermore, the fraction of crop residues collectable for biorefining depends on the weather, environmental constraints, types of crops, crop rotation, soil type, existing soil fertility, slope and extent of sloped land, tillage practices, and value judgment (Kadam and McMillan; Ho (1985a); Flaim; Glassner, Hettenhaus and Schechinger). The fraction of crop residues collectable for biorefinery conversion has varied in different studies reviewed. Kadam and McMillan and, Kim and Dale assumed that due to uncertainties of local situations 40% of available crop residues could be reasonably harvested on a sustainable basis. On the other hand, Kaylen et al., using a conservative approach, assumed 10% removal of crop residues was reasonable. Flaim reported that most soil scientists agree that tillage practices adopted by farmers largely determine the amount of crop residues that could be safely harvested as feedstock for biorefinery processing. Flaim found that in north-central Oklahoma, with conventional tillage, about 60% of available crop residues could be safely harvested as a biomass feedstock, and with conservation tillage 80% could be reasonably harvested. For Iowa, the percentages were slightly higher at 65% and 86% for conventional tillage and conservation tillage, respectively.

In their study, Glassner, Hettenhaus and Schechinger noted that the sustainable amount of crop residues collected from land depended on soil, topography, type of crops, crop rotation, tillage practice, and environmental constraints. They reported that to comply with USDA guidelines for soil erosion control a minimum of 30% of crop residues were required for surface coverage. They concluded that, with conservation tillage practice and being conservative, collecting 0.5 tons/acre of crop residues from 1.5 tons/acre of available residues in many areas could comfortably attain USDA erosion compliance. With no-till practice they found that the quantity harvested could likely be doubled.

Sokhansanj et al. stated that depending on harvest system as much as 80% of corn stover could be harvested. He, however, noted that harvesting large quantities of crop residues might be undesirable since crop residues left in the field serve to reduce erosion, contribute to organic matter and conserve moisture. Glassner, Hettenhaus and Schechinger stated that proper management of crop residue could result in a win-win situation for the producer, processor, and the environment. They reported that up to 75% of crop residues decompose and produce carbon dioxide, which is a greenhouse gas. They wrote that excessive amounts of crop residues on land made no-till farming difficult and reduced crop yield. Large quantities of crop residues that are not collected off land also resulted in decreased soil temperatures, slowing field drying, retarding germination, and reducing growing seasons (Glassner, Hettenhaus and Schechinger). Glassner, Hettenhaus and Schechinger also found out that excessive crop residues harbor pests and diseases, lead to blooming of weeds, and produce nitrogen leading to increases in nitrates and nitrogen oxides emissions into the atmosphere. They concluded that farmers and the biomass processing industry could benefit from conversion of excess corn stover to fuels and other products. The farmers might improve their profits through corn stover sales and reduced cultivation costs. The biomass biorefinery processors increase their profits through increased energy production to meet a growing energy market and production of other additional products. While the environment benefits from improved agricultural practices and fewer greenhouse gas emissions. Currently the economics of processing crop residues into energy do not show economic feasibility.

Ho (1985a) observed that with some crop residues, like rice straw, finding ways to dispose of them is a necessity since they tend to hamper proper cultivation. He reported that producing energy and other bio-products from the straw could in fact solve two problems simultaneously. He noted that there were other means of controlling soil erosion besides leaving crop residues in the field. Farmers could take advantage of existing agronomic and engineering practices to manage their soils to ensure long-term productivity. Ho wrote that agronomic factors included the type of crop grown, crop rotation, and sequence and tillage practices. Engineering practices included contouring, strip-cropping and terracing. If these practices were properly carried out they could result in permanent maintenance of soil productivity through decreased soil erosion. Even though agronomic and engineering practices could be used to control soil erosion, some crop residues should be left on land for other benefits besides erosion control. Ho stated that if all available crop residues were to be harvested, the selling price should be high enough so as to adequately cover the cost of soil erosion control on land requiring it. It would be necessary for large biorefineries that utilize crop residues to take the initiative in ensuring the maintenance of long-term soil productivity so as to have an adequate and steady flow of crop residues.

Some common indicators of lack of crop residues on land are increased soil erosion, lost nutrients, reduced soil organic matter, and decreased moisture-holding capacity of the soil (English et al). English et al. wrote that the effects of removed crop residues might impose both short- and long-run economic costs. They, however, observed that for a successful analysis of these economic costs, both direct and indirect costs must be considered. They defined direct costs as those costs attributed to harvesting, transporting, and processing the residues plus the agronomic costs of nutrient replacement. On the other hand, the indirect costs included the costs incurred due to cropping pattern shifts by farmers. The big challenge lies in determining the agronomic costs of nutrient replacement, due to removal of crop residues, which could give a true value of crop residues.

## The Monetary Value of Crop Residues

It is anticipated that land owners would expect to be compensated for the crop residues removed from farmland. The premium paid to farmers ($ cost/ton) would be expected to be sufficient to compensate for any lost nutrients or environmental impacts (e.g. soil erosion, loss of water holding capacity due to loss of organic matter). Sokhansanj et al. observed that variable costs associated with processing of biomass were sensitive to the cost of the feedstock. They noted that logistical issues such as storage, feedstock steady flow and uniformity in feedstock quality (such as composition, dirt and moisture content) were also important issues to be addressed in using corn stover and other crop residues. They wrote that corn stover biorefining technology represented challenges and opportunities for agricultural engineers and farm machinery industries.

In their study of the use of corn stover as biorefinery feedstock, Glassner, Hettenhaus and Schechinger reported a delivered price of corn stover of $34.76/dry ton if about 3 tons/acre were collected. If only 1.5 tons/acre were harvested, the price increased to $39.30/dry ton. Out of this, the baler received $16.06/dry ton and the producer and the hauler shared the remainder based on hauling distance to the processing plant. If more than 2 tons/acre were collected, out of $34.76 per dry ton, the producer received $12.00/dry ton for a hauling distance of 0-16 miles. The price received by the producer lowered as the hauling distance increased. At a hauling distance of 50-102 miles, the producer received $3.19/dry ton out of the delivery price of $34.76/dry ton. They reported that improvements on baling productivity and transportation efficiency were projected to lower the delivery cost to less than $25/dry ton delivered. They stated that cost reduction could improve infrastructure development for biomass collection and enhance energy crop production.

Literature review on removal of crop residues for off-field use reported in English et al. showed that a number of authors have suggested that non-legume crop residues have little value on land except in controlling erosion. Nevertheless, English et al. reported that the major nutrients (phosphorus, potassium, and nitrogen) should be replaced if removed to avoid long-term loss of soil fertility. English et al. used discounted present value of nutrients to determine the fertilizer value of crop residues. They did so because crop residues decay over a long period of time gradually releasing nutrients. They used a “decay schedule” to get the amounts of nutrients mineralized in a year and estimate the discounted present value. They reported the discounted present value of nutrients per ton of crop residue removed by crop in 1975 dollars using a 10% discount rate. The reported present values for corn, sorghum, soybeans and wheat were $4.38, $4.22, $5.34 and $2.79, respectively. They paid the farmers $9.69 per ton when 20% of energy from residues replaced that supplied by coal and $8.52 per ton when 60% of residues were used. The payment to farmers included the agronomic costs of nutrient replacement and cost of harvesting crop residue.

Ho (1985b) studied the economics of harvesting crop residues for production of methane via the dry fermentation route in the state of New York. He reported that the price paid for crop residues would be affected by the opportunity cost for bedding and/or animal feed and the fertilizer value of the residues. An established market for biomass including crop residues does not exist. Consequently price determination for crop residues may be achieved by using the cost of harvesting and transportation (Ho, 1985b).

For residues harvested using farmers' equipment, Ho found that a price that includes operating cost, compensation for nutrient loss and a 15% profit margin would range from \$17.50 - \$19.90 per oven dried ton. At this price the farmer received \$10.10/dry ton as compensation for nutrient loss. Considering harvesting using machinery owned and operated by a central facility, Ho reported that the price of crop residues would be \$17.50 per dry ton with the farmer receiving \$9.50/dry ton as compensation for harvesting crop residues and resultant nutrient and humus loss. This price does not include transportation cost to the processing facility. He observed that with these estimates very little of the crop residues in New York State were economically harvestable.

"Using crop residues for energy imposes two sets of costs: those incurred in actually collecting the residues and delivering them to the point of use, and the value foregone in no longer using them in their previous use" (Lockeretz, page 72). Lockeretz analyzed the various components comprising the value of crop residues. He reported four different classifications of costs associated with using crop residues. These included:

1. *Cash vs. opportunity costs*: a cost that results in actual expenditure of money compared to foregone value of residues, such as loss of plant nutrients.
2. *Direct vs. indirect costs*: this include direct consequences of harvesting residues, such as soil erosion and indirect effects such as loss of nutrients through increased loss of nutrient-rich topsoil.
3. *Immediate vs. deferred costs*: this definition includes costs incurred in present season compared to those that accrue over many years.
4. *Private vs. social costs*: this compares costs borne by the farmer and those incurred by the local society or the nation as a whole.

Lockeretz wrote that residual removal reduced soil organic matter both directly and indirectly through increased erosion of topsoil rich in organic matter. Lockeretz further reported that the primary nutrients in one ton of corn stover were worth approximately \$10/ton if valued at commercial fertilizer prices. The cost incurred by farmers in harvesting crop residues was reported to be in the range of \$15 to \$30/ton. This estimate did not include compensation to the farmer for the benefits of residues lost. He stated that the total cost of residues could be significantly underestimated. He concluded that if the farmer accepted lower prices a misallocation of resources would occur, both from the farmer's own viewpoint as well as that of society as a whole. He suggested that harvesting of crop residues should ensure that government renewable energy policies are coordinated with soil conservation programs.

Gallagher et al. estimated the supply and social costs for harvesting crop residues in the United States. They reported the opportunity costs of using crop residues for biorefinery processing. In their report they observed that indirect fertilizer costs account for the major cost item when residues were harvested. They noted that unused residues provided essential nutrients like phosphorus, potassium, and nitrogen for the subsequent crop. For the two crop residues considered in their study, the costs of replacing fertilizer associated with residue harvest, using 1997 prices, were \$6.47 per ton for corn, and \$4.99 per ton for wheat. They noted that in areas with livestock enterprises crop residues may be used as livestock feed. For such areas where crop residues are used as livestock feed, they estimated the opportunity cost of harvesting crop residues for alternative uses. They reported that quality discounts were done based on variation in the protein content of the residues.  For the two crop residues in their study, the 1997 values of using residue as livestock feed were $41.90/ton for corn, and $21.21/ton for wheat.

## Energy Balance

Energy balance or net energy value is defined as energy content of ethanol minus fossil energy used to produce ethanol (Shapouri, Duffield and Wang).  Concerns have been raised regarding the energy balance of corn-ethanol biorefinery processing.  Critics have reported that the fossil energy that is used to grow, transport and process corn into ethanol is greater than the energy content in the produced ethanol fuel (Shapouri, Duffield and Wang).  On the other hand, proponents have shown that the energy value present in ethanol is greater than the energy expended to produce ethanol.  The energy consumed to produce ethanol includes energy expended in growing the corn, harvesting, transporting, and processing it into ethanol.  Reports on energy balance exhibit a considerable amount of variation in the findings.  These variations relate to various assumptions about corn yields, ethanol conversion technologies, fertilizer manufacturing efficiency, fertilizer and pesticides application rates, coproduct evaluation, and the number of energy inputs included in the calculations (Shapouri, Duffield and Wang; Chambers et al.; and Henke, Klepper and Schmitz).  Shapouri, Duffield and Wang noted that the time period for which information was collected and the study was conducted determined the type of results obtained.  They reported that various researchers have used data from different time periods and noted that energy use efficiency of manufacturing plants, such as fertilizer and ethanol plants, have improved over time.  They observed that studies that used older data had a tendency to overestimate energy required because ethanol manufacturing and farm production technology have become increasingly energy efficient over time. They also reported that energy required by the ethanol biorefinery facilities differed greatly among the studies. They wrote that since reports often lack certain details on their calculation procedures it was often difficult to determine the source of variations in the results from different studies.

Pimentel (1991) reported that “ethanol production is energy inefficient, requiring considerably more energy input than is contained in the ethanol produced” (Pimentel, page 2). He reported that the total energy input required to produce a gallon of ethanol was 131,017 Btu. A gallon of ethanol has an energy value of 76,000 Btu. He therefore concluded negative energy balance. Even after including energy credits for coproducts with total energy ranging from 11,000 Btu/gal to 32,000 Btu/gal, Pimentel still estimated a net energy loss. He concluded that “…ethanol production would increase U.S. need for fossil fuels, rather than decrease U.S. dependence on fossil fuels” (Pimentel, page 10). Pimentel’s data assumptions differed with assumptions from most current studies. He assumed a lower corn yield and the nitrogen fertilizer application rate as well as energy required to produce a pound of nitrogen fertilizer were both higher than other studies. Shapouri, Duffield and Wang reported that another major difference between Pimentel’s findings and most other studies was that the estimates he used in his study included energy expended on capital equipment like steel, cement, and other materials used to construct the ethanol plant. Most studies did not include energy expended in manufacturing of capital equipment.

In their paper, Keeney and DeLuca discussed the principal forms of bioenergy crops, including annual and perennial energy crops, cellulosic crop residues, and woody biomass. The data they used in their study included Iowa statistics on fertilizer and pesticide use on conventionally produced corn and data from a study by Pimentel et al. The collected data were used to estimate the energy required to produce corn in the Midwestern U.S. Except for corn yield and energy used in processing corn into ethanol, most of the other data assumptions were similar to those assumed by Pimentel et al. They reported a net energy deficit of approximately 8,435 Btu per gallon of ethanol. They observed that the corn-ethanol energy imbalance would be greatly reduced through more efficient use of process by-products and through reduction in energy required for corn production.

Chambers et al. performed a detailed analysis of energy inputs and outputs on grain-based gasohol (10% corn- ethanol, 90% gasoline). The major energy requirements included nonrenewable energy requirements at the biorefinery, on the farm, at the petroleum refinery, and energy required for all intermediate transportation. In their conclusion they stated that "…assuming the use of standard agricultural production techniques and conventional distillation technology the net energy balance for gasohol production is negative" (Chambers et al page 795). They observed that if, however, farming practices and industrial technologies with improved energy-use efficiency were developed, and if the distillation process was productive and efficient, it was possible to get a modest positive energy balance from the production of gasohol.

Parisi analyzed the energy balance for ethanol as a fuel and reported that the ratio of energy output to energy input was close to unity (i.e. 1.21). Included in the energy input were energy consumed in operating agricultural machinery, irrigation, producing chemical products, agricultural machinery amortization, transportation and truck amortization, processing of raw material into ethanol and plant amortization. Included in energy outputs were energy in ethanol, process byproducts, yeast, biogas and others.

The studies above show that energy balance for corn-ethanol is either negative or unity. Other studies, especially current studies, have reported positive energy balance values. Marland and Turhollow studied carbon dioxide emissions of fuel ethanol from corn. In their analysis of energy balance they reported a positive energy balance. Compared to results by Pimentel (1991) they assumed higher corn yields, lower nitrogen fertilizer application rates hence lower energy spent through nitrogen and they did not assume energy spent through capital equipment such as machinery and buildings. Their energy input analysis included energy spent through corn production and conversion of corn to ethanol.

Wang, Saricks, and Wu conducted a study on fuel-cycle fossil energy use and greenhouse gas emissions of fuel ethanol produced from corn from the four largest corn-producing states—Illinois, Iowa, Minnesota, and Nebraska. In their energy balance analysis they included energy required for farming operations, for manufacture of fertilizer and other farm chemicals, for transportation of fertilizer and chemicals from manufacturer to farms and transportation of corn to ethanol plants. They also included energy used for ethanol production. They assumed a high corn yield of 130 bushels per acre. They reported that recent wet milling large ethanol plants were equipped with cogeneration systems that produce both steam and electricity. They noted that this technology has reduced biorefinery plant energy use by as much as 30%. Therefore their assumed total energy consumption by ethanol plants was lower than energy consumption assumed by other studies i.e. 40,400 Btu/gal for dry milling plants and 40,300 Btu/gal for wet milling plants. They concluded that production and use of corn-based ethanol achieves net energy savings in the four states they examined.

Wang, Saricks and Santini conducted a study in which they estimated the impacts of ethanol produced from U.S. corn on fuel-cycle energy and greenhouse gas emissions. They reported that the U.S. corn yield per acre had increased over the past 30 years by over 50%, to about 125 bushel per harvested acre. They attributed this increase to better corn varieties, improved farming practices, and farming conservation measures. They reported that despite the increase in the corn yield the per-acre fertilizer and energy inputs for corn farming had stabilized or declined slightly over the past 15 years. They observed that modern ethanol plants were generally more energy efficient than old biorefinery plants. They estimated that, for near-term future ethanol plants, continuing improvements on energy use efficiency would result in an energy use rate of 36,900 Btu/gal for modern dry milling plants and 34,000 Btu/gal for modern wet milling plants. In estimating energy output they accounted for co-products. A gallon of ethanol has an energy content of 76,000 Btu. Subtracting the estimated total energy required to produce the gallon of ethanol from the energy contained in the gallon of ethanol they estimated that corn-based ethanol had a net energy balance of 20,000-25,000 Btu per gallon. They reported that the positive net energy balance for corn-based ethanol was as a result of the improvements in corn farming and corn-to-ethanol conversion technology achieved over the past 20 years.

Shapouri, Duffield and Wang reviewed the methodological differences among different studies on energy balance of corn ethanol with the purpose of identifying the cause of inconsistencies among study results. They reported that current higher corn yields, lower energy required per unit of output in the fertilizer industry, and improvements in ethanol fuel conversion technologies have greatly enhanced the energy efficiency of producing ethanol compared to several years back. They concluded that corn-based ethanol was energy efficient as shown by an energy output to input ratio of 1.34. They also concluded that the net energy balance of corn-based ethanol had been increasing over the years because of technological improvements in corn-to-ethanol conversion and increased efficiency in farm production.

Shapouri, Duffield and Wang observed that studies that used older data tended to overestimate energy use because the efficiency of growing corn and converting it to ethanol had been improving significantly over time. They reported that most studies included only primary energy inputs in their estimates of net energy balance. They reported that secondary energy inputs, such as energy required to build ethanol facilities, farm vehicles, and transportation equipment were extremely difficult to quantify. They stated that secondary inputs would account for very little energy on a per gallon of ethanol basis because the energy contained in fixed inputs, such as the cement used to build the plant, would have to be distributed over total production (including coproducts) during the lifetime of the facility. They also stated that in case of farm production, the energy value contained in farm equipment would have to be distributed across all crops (including crops not used for ethanol production) for which the equipment was used over the lifetime of the equipment. Table 3 summarizes the energy balance results from a few different studies as reported by Shapouri, Duffield and Wang.

Ethanol can be obtained from several agricultural products. The most important sources are sugarcane in Brazil and corn in the USA (Ortiz-Cañavate). Ortiz-Cañavate wrote that in Europe major sources of ethanol were cereals particularly wheat, sugar beet, and sweet sorghum. Ortiz-Cañavate studied the use of sugar beet to produce ethanol (in Spain) and found that the energy balance was 1.3. Henke, Klepper and Schmitz using the same feedstock (sugar beet) in their study in Germany reported an ethanol energy balance of 0.65. For sweet sorghum, Worley, Vaughan and Cundiff reported an energy balance of close to unity in their study. On the other hand, a study by Macedo reported output/input energy ratio of 9.2 for ethanol produced from sugarcane in Brazil.

As the case with ethanol from sugarcane, it is believed that producing ethanol from lignocellulosic biomass is potentially more energy efficient than producing it from corn grain. Cellulosic materials are more widely available and the energy input for producing LCB feedstock is much lower than for corn grain (Lynd et al.). Lynd et al. reported the potential energy balance for processing of lignocellulosic biomass into ethanol fuel. They reported a mathematical equation for obtaining the ratio of energy output to energy input, *R*, for LCB as

$$R = \frac{1 + (3 * E)}{A + T + C + D + P} \tag{1}$$

where *E* is exported electricity, *A* is agricultural inputs, *T* is raw material transport, *C* is chemical inputs, *D* is distribution, and *P* is plant amortization. The 1 in the numerator represents ethanol and the multiplier of *E* reflects the displacement of thermal energy for conventional power generation. Using the above equation they found that the energy balance (*R*) of ethanol from LCB was 5. They reported that an important factor in accounting for the energy value of ethanol production from LCB is the energy available from residues remaining after fermentation (Lynd et al.). They stated that unfermentable raw materials, such as lignin, could be mechanically dewatered and burned to provide

**Table 3. Energy Input Assumptions of Corn-Ethanol Studies**

| Study/Year | Corn Yield | Nitrogen fertilizer application rate | Nitrogen fertilizer production | Corn ethanol conversion rate | Ethanol conversion process | Total[1] energy use | Coproducts[1] energy credits | Net[1] energy value |
|---|---|---|---|---|---|---|---|---|
| | *Bu/acre* | *lb/acre* | *Btu/lb* | *gal/bu* | *Btu/gal* | *Btu/gal* | *Btu/gal* | *Btu/gal* |
| Pimentel (1991) | 110 | 136 | 37,551 | 2.50 | 73,687 | 131,017 (LHV) | 21,500 | -33,517 |
| Pimentel (2001) | 127 | 129 | 33,547 | 2.50 | 75,118 | 131,062 (LHV) | 21,500 | -33,562 |
| Keeney & DeLuca | 119 | 135 | 37,958 | 2.56 | 48,470 | 91,196 (LHV) | 8,078 | -8,438 |
| Marland and Turhollow | 119 | 127 | 31,135 | 2.50 | 50,105 | 73,934 (HHV) | 8,127 | 18,154 |
| Lorenz and Morris | 120 | 123 | 27,605 | 2.55 | 53,956 | 81,090 (HHV) | 27,579 | 30,589 |
| Ho (1989) | 90 | NR | NR | NR | 57,000 | 90,000 (LHV) | 10,500 | -4,000 |
| Wang, Saricks & Santini | 125 | 131 | 21,092 | 2.55 | 40,850 | 68,450 (LHV) | 14,950 | 22,500 |
| Agri. and Agri-Food Canada (1999) | 116 | 125 | NR | 2.69 | 50,415 | 68,450 (LHV) | 14,055 | 29,826 |
| Shapouri, Duffield & Graboski | 122 | 125 | 22,159 | 2.53 | 53,277 | 82,824 (HHV) | 15,056 | 16,193 |
| Shapouri, Duffield & Wang | 125 | 129 | 18,392 | 2.66 | 51,779 | 77,228 (HHV) | 14,372 | 21,105 |

NR: Not reported

LHV: Low Heat Value = 76,000 Btu per gallon of ethanol. Keeney and DeLuca used 74,680 Btu per gallon of ethanol.

HHV: High Heat Value = 83,961 Btu per gallon of ethanol. Lorenz and Morris used 84,100 Btu per gallon of ethanol.

[1] The midpoint or average is used when studies report a range of values.

Source: Shapouri, Duffield and Wang.

30,000 to 40,000 Btu per gallon of ethanol. They reported that this amount was in excess of processing energy requirements for current designs with a wood feedstock. They noted that the excess energy could be used to produce electricity in a cogeneration with ethanol.

Wang, Saricks and Santini found that the net energy balance for LCB-to-ethanol conversion technology was over 60,000 Btu per gallon. They reported that the large positive net energy balance for LCB-based ethanol was largely attributable to two factors. First, there is low use of nonrenewable energy in biomass farming and LCB-to-ethanol conversion. Second, they assumed that the extra electricity generated by the LCB-to-ethanol biorefinery plant would be exported into the electric grid to displace some electric energy from the electric power plants. Similarly, using switchgrass as a feedstock for ethanol production in their study, McLaughlin and Walsh reported that the energy output/input ratio for ethanol was 4.43.

Similar results have been observed when woody biomass was used as feedstock for ethanol production. Foster used short rotation coppice as an energy crop for ethanol production and reported that energy output was 30 times greater than energy input necessary for fuel production and transport. Similarly, Pimentel and Rodrigues observed that the energy input/output ratio for a woody biomass system was 1:3.

## Summary

The reviewed literature leads to four major points. First, there are abundant lignocellulosic biomass resources available in the United States that could be harvested for biorefinery processing. Unlike most of the reviewed studies that considered one or a few biomass species, this study considers a variety of biomass species.

Second, the method and assumptions for accounting for biomass harvesting cost may substantially affect the estimated harvest cost and hence the total delivery cost of biomass feedstock to a biorefinery. It is anticipated that accounting for harvesting cost exogenously versus endogenously may give varying harvest and delivery cost estimates. Endogenously accounting for LCB harvest cost may provide cost estimates that are closer to the actual industry costs. It is also important to take into consideration the availability of harvest days since these are affected by weather and seasonal changes. Changes in weather affect the ability of machinery to go in the field to harvest. It is important that a well coordinated LCB harvest structure should develop in concert with the biomass biorefinery industry. The review has shown that custom harvesting rates are higher than those of a coordinated harvest system managed by the biomass industry. The study by Thorsell et al. revealed that a coordinated set of harvest machinery with personnel (harvest crew) that harvest biomass over a large land area would attain economies of size.

Third, the arguments presented in this review furnish evidence of untapped reliable sources of biorefinery feedstock. A big potential for production of LCB feedstock for biorefinery processing may exist on CRP lands. To ensure the use of these feedstock resources does not defeat the main purpose of the CRP program some regulations have to be put in place. The proportion of biomass harvested and frequency of harvest may be important issues to be considered. The interaction between these regulations and the economics of using the LCB feedstock resources for biorefinery production is the interest of this paper. The review also shows that crop residues exist in adequate supplies in some regions for biorefinery processing. Crop residues as a biorefinery feedstock pose several challenges including harvesting problems and environmental consequences of removing them. Among the studies that have investigated crop residues as feedstock for biorefinery processing, no study has conducted a comprehensive and thorough feasibility analysis of a biorefinery plant that includes purchase, harvest, transportation, and processing costs of crop residues.

Fourth, theoretically the energy input and output ratio for the biomass-to-ethanol processing technology is believed to be substantially greater than 1, while that of grain-to-ethanol processes, depending on study assumptions, varies from less than 1 to slightly above 1. Hence , in terms of energy balance, the biomass-to-ethanol process may be more promising than the current grain-to-ethanol industry but there is need to develop more valuable bio-products from LCB processing besides ethanol. The following section gives the theoretical model for the research study.

# CHAPTER III

# CONCEPTUAL FRAMEWORK

New technologies for producing biobased products including ethanol are being developed that are based upon the use of low value LCB such as crop residue and perennial grasses. 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. Success of an LCB-based system rests on its ability to pay for the costs incurred and retain some profits. In this regard, low value feedstock such as crop residues and herbaceous feedstock from grasslands, pastureland and land enrolled under CRP would be an added advantage. The use of LCB to produce bioproducts calls for large quantities of biomass feedstock, which entail high costs of harvesting and transportation. Lack of a coordinated infrastructure for biomass feedstock harvest and storage such as custom harvesting may lead into either improperly accounting for harvest costs or encountering high costs of harvesting due to loss of economies of size. As a business venture, the biorefinery industry must be competitive to succeed, hence any investment analysis is essential to determine conditions necessary for feasibility.

The biorefinery technology proposed in this study has the flexibility to use crop residues (wheat straw, corn stover), native prairies, improved pastures (bermudagrass, tall fescue, old world bluestem), and a dedicated energy crop (switchgrass) as feedstock. Harvest windows differ across species of feedstock enabling the use of coordinated harvest and collection machinery units throughout many months. Second, the feedstock has to be transported to optimally located processing plants. Third, the machinery units as well as plant location must be endogenously determined by the model. In addition, several constraints must be assumed to effectively compute the model.

Because of the number of variables and constraints and the requirement to handle complicated spatial and temporal (harvesting and storage) relationships, agricultural processing plant location models are mostly analyzed with mathematical programming techniques (Tembo). Floudas defines mathematical model as a set of related mathematical functions whose purpose is to simulate the response of the system being modeled. He wrote that a linear mathematical model consists of solely linear functions; a nonlinear mathematical model involves one or more nonlinear functions. A brief discussion of optimization techniques and solution algorithms follows.

Floudas gives an overview of a general mathematical programming model. In general, mathematical programming models consist of the following four key elements: parameters, variables, constraints and mathematical relationships. Parameters are fixed to one or multiple specific values, and each fixation defines a different model. Variables, by definition, can take on different values and these values can be continuous, integer, or a mixed set of continuous and integer. The constraints are fixed quantities by the model statement. Constraints can be equality or inequality depending on problem modeled. The mathematical relationships can be algebraic, differential, or a mixed set of algebraic and differential constraints, and can be linear or nonlinear. To attain the objectives of a firm the mathematical programming model can be optimized (i.e. maximized or minimized).

An optimization problem is a mathematical model that contains one or multiple performance criteria in addition to the aforementioned elements (Floudas). The performance criterion is denoted as the objective function, and it can be the minimization of cost or maximization of profit. A typical mixed integer optimization model may be of the form:

$$\max Z = \sum_{j=1}^{n} c_j X_j + \sum_{k=1}^{m} d_k Y_k \tag{3.1}$$

$$s.t.$$

$$\sum_{j=1}^{n} a_{ij} X_j + \sum_{k=1}^{m} a_{ik} Y_k = 0 \qquad \forall i,k \tag{3.2}$$

$$\sum_{j=1}^{n} a_{ij} X_j + \sum_{k=1}^{m} a_{ik} Y_k \leq 0 \qquad \forall i,k \tag{3.3}$$

$$X_j \geq 0, \quad \forall j \tag{3.4}$$

$$Y_k \in \{0,1,2,3,...\} \text{ integer variables} \tag{3.5}$$

where $Z$ is the objective function value to be optimized, $c_j$ and $d_k$ are gross margins of a unit of *jth* and *kth* variables, $X_j$ are continuous variables, $Y_k$ are integer variables, $a_{ij}$ and $a_{ik}$ are input-output coefficients. Equation (3.1) is the objective function, equation (3.2) are equality constraints, equation (3.3) are inequality constraints, (3.4) are nonnegativity constraints, and (3.5) are integer variable constraints (Floudas).

Formulation (3.1) contains a number of classes of optimization problems, by appropriate consideration or elimination of its variables. If the integer variables are zero, and the objective function and constraints are linear, then (3.1) becomes a linear programming (LP) problem. If the integer variables are zero, and there exist nonlinear terms in the objective function and/or constraints, then (3.1) becomes a nonlinear programming (NLP) problem. If there exists a number of integer variables, the integer variables participate linearly and separable from the continuous variables, and the objective function and constraints are linear then (3.1) becomes a mixed-integer linear programming (MILP) problem. If there exists a number of integer variables, and there exist nonlinear terms in the objective function and constraints then (3.1) becomes a mixed-integer nonlinear programming (MINLP) problem (Floudas).

A large number of optimization problems constitute continuous and integer variables which appear linearly, and hence separable, in the objective function and constraints. These mathematical models are denoted as Mixed-Integer Linear Programming (MILP or MIP) problems. In many applications of MIP models the integer variables are 0-1 variables (i.e. binary variables). MIP models have seen wide applications in facility location problems, allocation problems, scheduling problems, and fixed-charge network problems (Floudas). The biomass biorefinery problem presented in this paper is a mixed-integer linear programming (MIP) problem since it has both continuous and integer variables that appear linearly in the objective function and constraints. For instance the quantities of biomass harvested and bioproduct produced are continuous variables while the numbers of machinery units and processing plants are integer variables. The construction of processing plants is a binary variable (i.e. 0-1 variable). Either it is economical to construct a plant in that location (value of 1) or uneconomical to construct a plant in the location (value of zero).

Several algorithms have been proposed for mixed-integer linear optimization programming problems. Floudas lists four major algorithms that have been proposed in the literature: branch and bound methods, cutting plane methods, decomposition methods, and logic-based methods. In large-scale mixed-integer linear programming solvers, branch and bound methods are the most commonly used algorithms. In the General Algebraic Modeling System (GAMS), CPLEX is the solver commonly used for MIP problems and it uses the branch and bound algorithm.

Application of a linear programming model can be found in a study by English, Short and Heady. They studied the economic feasibility of crop residues as auxiliary fuel in coal-fired power plants in Iowa. The crop residue considered in their study was corn stover. They used linear programming that was divided into two main components of production and crop residue use. The linear programming model was formulated to maximize net returns to crop production in Iowa and minimize the costs of supplying coal and crop residues to Iowa power plants.

Applications of a linear mathematical model can also be found in Nienow et al. In their study of economic evaluation of biomass co-firing with coal in electricity production in Northern Indiana they used a linear mathematical model to minimize the variable cost. The cost was minimized subject to environmental regulations, process constraints, and fuel prices. The biomass feedstock considered in their study was woody biomass (*Salix* trees).

Kaylen et al. studied the economic feasibility of producing ethanol from lignocellulosic feedstock in Missouri. In contrast to the study by Nienow et al., they built a non-linear mathematical optimization model using GAMS. Since the study involved analyzing long-term investment, they used net present value (NPV) to estimate the time value of money from a ‘stream of net income’ over a period. The feedstock considered included crop residues, woody biomass, and dedicated energy crops.

Tembo, Epplin and Huhnke used a multi-period, multi-region, mixed-integer mathematical programming model in an investment appraisal study. Their objective function was to maximize the net present worth of a biomass biorefinery industry assuming fifteen years plant life. Unlike the other studies, they assumed a variety of biomass feedstock including crop residues, native prairie grasses, improved pastures and introduced grasses.

Not all studies of the economic feasibility of an LCB biorefinery have used mathematical programming models. Nilsson used a simulation model to design a straw delivery system. Due to climatic, geographical, agronomic, technical and economic aspects, straw handling could be a complex and difficult task. Nilsson concluded that simulation was a powerful experimentation tool to identify bottlenecks and analyze the behavior and performance of straw fuel delivery system. Graham, English and Noon used Geographical Information System (GIS) to estimate the cost and environmental implications of supplying specific amounts of energy crop feedstock to a biorefinery. They found GIS advantageous in modeling biomass due to environmental effects and geographical variability in factors that affect the supply and cost of biomass for biorefinery. However, they noted that the reality depicted in a GIS model tends to be static rather than dynamic.

The biomass biorefinery problem of this paper is viewed as a business investment venture in which investors may be interested to maximize returns to their investments. Since the industry will involve large capital outlays at the beginning of the project the use of net present worth in the analysis seems plausible. But net present worth assumes plant construction, location, and many more variables are exogenous to the model. This allows us to adapt commonly used techniques, i.e. mixed-integer programming in mathematical programming model, along side the net present worth. Tembo stated that one way to circumvent the shortfalls of these two approaches is to incorporate NPW as an objective function in a plant location optimization model as done in this study.

# CHAPTER IV

# PROCEDURES AND DATA SOURCES

## Procedures

### Economic Modeling

In this study the economic model is designed and used to answer a number of very specific questions about the economics of an LCB biorefinery. Some of the questions the model would attempt to answer are:

- Where would LCB be produced?
- What biomass feedstock or combination of feedstock is economically optimal?
- What level of fertilizer is optimal?
- How much of which species should be harvested in each period (month)?
- How many acres will be harvested in each month and year?
- How many harvest machines would be required to harvest the biomass?
- What is the effect of the available number of harvest days on the cost to deliver a continuous flow of biomass to a biorefinery?
- What quantity of LCB should be placed in field storage in each period (month)?
- What quantity of LCB should be placed in storage at the biorefinery in each period (month)?

- What quantity of LCB should be removed from each storage location in each month?
- What is the optimal transportation flow of LCB from the field storage and to the biorefinery?
- What would be the minimum cost to deliver LCB to the biorefinery?
- What would be the optimal size and location of the biorefinery?
- From what distance would LCB be transported to the biorefinery?
- Modeling could be of great use in circumstances like these.

Proper understanding and correct modeling of the problem may give insight into the solutions while offering proper policy direction.

Figure 1 is a schematic chart of levels of decision making in the LCB conversion industry. The model in this study has to go through all these decision levels before giving the optimal and feasible solution. In this chart the model makes a choice among the 77 biomass supplying counties in Oklahoma. Each supplying county has the potential to supply any of the nine biomass species. The question is which species are optimal? Some species especially dedicated energy crops and improved pastures need fertilizer to be applied. How much fertilizer should be applied? Since biomass will deteriorate in the field if not harvested on time, the next level of the schematic view asks which months are optimal to harvest (HARV) and the optimal number of harvest machines? Having harvested biomass feedstock, how much of it should be put in field storage (FST) and how much should be shipped to the biorefinery (BIORF) in each month? Notice that each activity falls under a particular month. While at the biorefinery, how much should be put in the biorefinery storage (BST) and how much should be sent for processing to

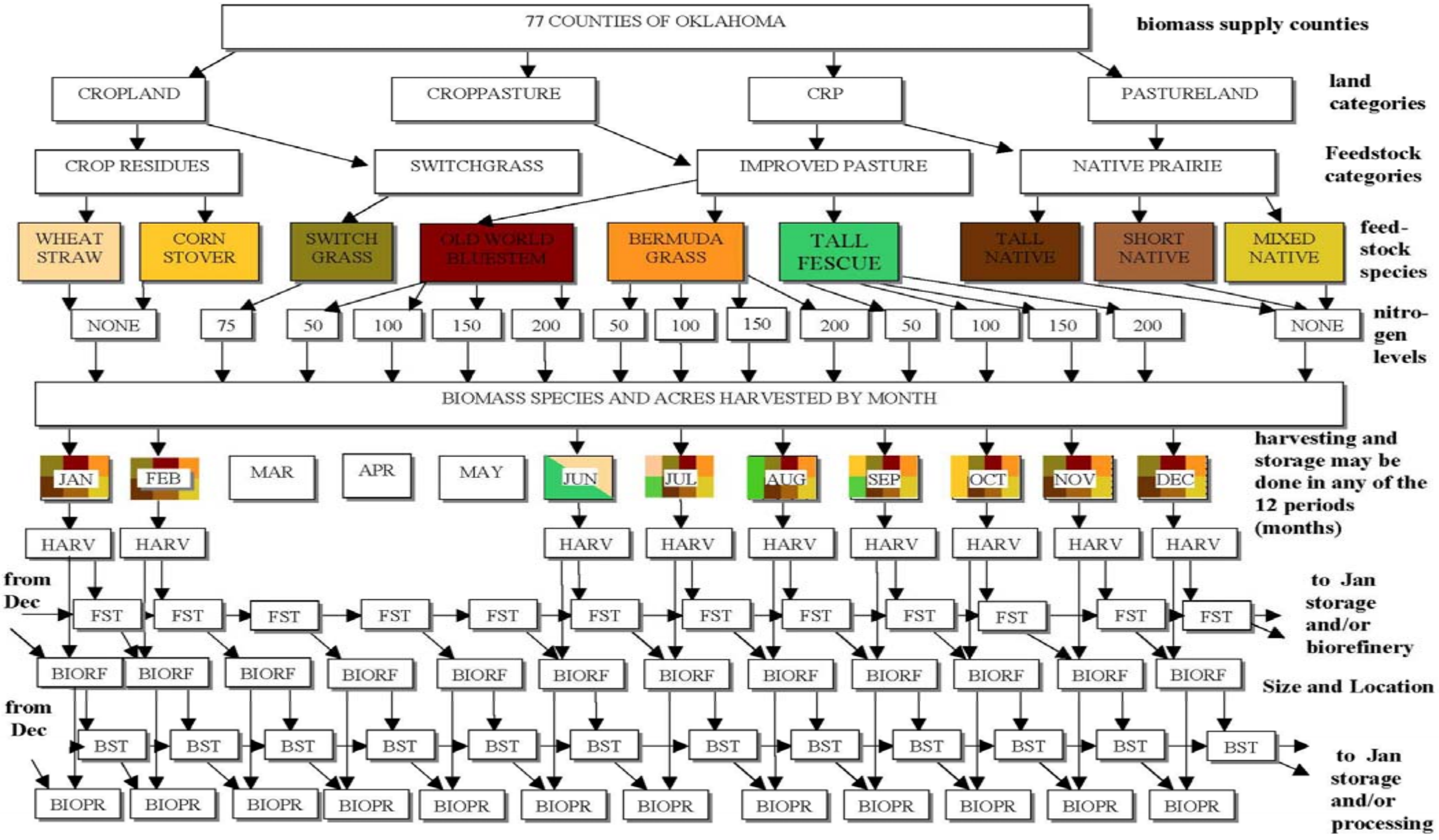


**Figure 1.** Schematic view of levels of choices made in LCB conversion industry

operate at full capacity. This also has to be done in each month. The rest of the chapter gives the model formulation, data and assumptions employed.

## Background Information of the Study Model

This study builds upon the work of Tembo (2000) and Thorsell (2003). Previously, Tembo noted that a well-developed harvesting and transportation system does not exist for LCB. Tembo built a multi-region, multi-period, mixed integer mathematical programming model to identify key cost components, potential bottlenecks, and reveal opportunities for reducing costs and prioritizing research. Tembo's model differed from prior studies in several respects. His model and case study considered (i) a variety of feedstock; (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 feedstock have different harvest windows and that the dry matter yield of species depends upon the time (month) of harvest; (iv) recognized 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 and types of LCB stocks and flows, location of biomass production, fertility regime(s), harvest structure and month(s), biomass storage, biomass shipment networks, and the most important cost items in the system. Tembo used his model to determine for specific regions in Oklahoma the most economical source of

LCB, inventory management, biorefinery size, and biorefinery location as well as the breakeven price of ethanol using a theoretical gasification-fermentation process.

Tembo's model was innovative but contained few shortcomings. Two of these result from the method used to estimate harvest cost. A third shortcoming results from the method used to compute feedstock procurement cost.

Tembo used conventional agricultural machinery cost estimation software to compute LCB harvest 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 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. Therefore 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, by his modeling method the estimated cost to harvest a ton of prairie grass ranged from $4.10 to $18.35. For a good description of Tembo's assumptions on harvest structure and costs refer to Appendix A, Tables 17 through 19.

Based on the assumption of harvest cost per acre, the model determined that it was optimal to harvest more than 50% of total LCB tonnage required for an entire year in the month of September. Tembo assumed that the market would provide harvest machines in a timely manner. However, the assumed capacity does not currently exist and a large investment in harvest machines would be required to achieve the capacity necessary to harvest the annual quantity of required LCB in a short time period. In effect, Tembo's assumption on harvest structure did not appropriately account for harvest costs.

A third shortcoming results from the method used to account for procurement costs. Tembo assumed that the biorefinery investors would engage in long-term land leases. He assumed that native prairies could be leased for \$20 per acre per year, improved pastureland for \$40 per acre per year, and cropland for \$60 per acre per year. Since the expected yield of native prairies ranged across the state from 0.67 to 3.0 tons per acre, the effective procurement cost for biomass from native prairies ranged from \$29.85 to \$6.67 per ton. Procurement costs for other species also varied substantially with yield. Refer to Table 20 in Appendix A, which gives Tembo's assumed land rent, biomass opportunity cost, and other costs in dollars per acre per year.

Thorsell designed a coordinated harvest unit that provides a capacity to harvest a given number of tons of biomass per time period. The harvest unit, which consists of a coordinated set of harvest machines including mowers, rakes, balers, tractors, and a bale transporter, provides a throughput capacity. Her coordinated harvest unit may result in substantial size economies associated with harvest machines. Her cost estimates were developed under the assumption of the coordinated set of harvest machines operated by specialized harvest crews that harvest from June through February. Field speeds of machines could be adjusted with crop yield to achieve the throughput capacity.

This study differs from prior studies in several respects. First, in the present study the harvest unit as designed by Thorsell is incorporated into Tembo's model as an integer and endogenously chosen activity. Thus the model can endogenously choose the optimal number of harvest units that for an annual cost (depreciation, insurance, interest, taxes, repairs, fuel, oil, lubricants, and labor) provide capacity to harvest a given tonnage per month. A single harvest unit provides a capacity of 340.67 tons per day. Monthly capacity depends upon the number of harvest days per month and the number of endogenously determined harvest units.

Second, an estimate of the expected number of harvest days per month based upon historical weather patterns is incorporated. In his 1973 thesis, Reinschmiedt estimated available days for field work in each month in the western Oklahoma. These monthly field work days were estimated based on historical weather pattern. Kletke and Sestak used Reinschmiedt's findings to estimate available field work days for the state of Oklahoma. This study has assumed the reported field work days as potential days available in each month when harvesting could be done.

Third, Tembo's model is augmented so that the farmer/landowner can either be paid a fixed rate per ton for material harvested or be paid a fixed rate per acre for the rights to harvest the material. For CRP land, since landowners will receive a 25% reduction in payment for the acreage of land harvested, a payment per acre may be deemed necessary. This might be the first attempt to determine if the provisions included in the 2002 Farm Bill relative to harvest of LCB from CRP land are of value.

Fourth, Tembo's model is augmented so that biomass feedstock storage costs are not charged per ton per month but on a per ton basis regardless of the number of months the feedstock is kept in storage. Previously Tembo had assumed a field storage cost of $2/ton/month. In other months a certain quantity of biomass was carried over to the following month. Consequently, a given quantity of LCB carried over from month to month ended up incurring multiple storage costs. To avoid multiple storage costs on each ton stored this study assumes a storage cost per ton of biomass taken into storage.

Fifth, the coordinated set of harvest machines, defined as the harvest unit, is included as an integer investment activity in a multi-region, multi-period, mathematical programming model. The model includes alternative feedstock and harvest capacity constraints determined by the number of harvest days per month and the endogenously determined number of harvest units. The model breaks the year into 12 discrete periods (months) enabling a flow of feedstock to a biorefinery and recognizes that the expected dry matter yield of species depends upon the time (month) of harvest and that storage losses will occur and depend upon location of storage and time of storage. Except for Tembo's study, previous studies of the economics of LCB biorefinery processing did not use monthly time step as done in this study.

Sixth, results from the model with the integer harvest unit activities are compared with results from a conventional model that includes a fixed harvest charge assessed per ton and no harvest timing constraints. One of the objectives of this study is to determine if the method of accounting for harvest cost affects the estimated expected cost to deliver a ton of LCB to a biorefinery. Therefore in this study one model was solved with a coordinated set of harvest machines and harvest crew (called a harvest unit) as an endogenous integer variable. Another model was solved by assuming a harvest cost per ton as an exogenous variable. The differences in the results of the two models tell the effect of method of modeling harvest cost on the estimated delivery cost and other variable.

The model contains what McCarl and Spreen denote as sequencing activities in that harvest, storage, and transportation are sequenced to provide a flow of material to the biorefinery. The sequencing provides within-period dynamics. The model contains storage and inventory, in that LCB may be harvested and placed in storage in nine of the months and LCB may be removed from storage for use in each of the twelve months. Alternatively, LCB may be transported and processed in the harvest month. Decisions regarding LCB production, harvest, storage, transportation, and production of bioproducts are assumed made repeatedly in all years of plant life, what may be referred to as a representative single period. This type of model is appropriate when (i) resource, technology, and price data are assumed to be constant and (ii) a long-run steady state solution is acceptable. The location and size of the biorefinery are endogenously determined. However, all plant size and plant location decisions are made under the assumption that all investment takes place at the beginning of the 15-year (in the base model) life.

## The Mixed Integer Mathematical Programming Model

In this section, a full description of the model and data sources and assumptions are presented. Descriptions of all indices, parameters and variables used in the model are summarized in the list of symbols at the beginning of this dissertation. The integrative investment appraisal plant location, biomass production, storage and transportation optimization model as developed by Tembo was as follows:

$$\begin{aligned}\max_{q,x,xt,xs,A}\quad NPW = \Bigg\{ \sum_{m=1}^{M} \Bigg[ & \sum_{j=1}^{J}\sum_{s=1}^{S}\sum_{g=1}^{G} \rho_g q_{jsgm} - \sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{f=1}^{F}\sum_{h=1}^{H} \alpha_{kh} A_{ikfhm} - \sum_{i=1}^{I}\sum_{k=1}^{K} \gamma_k xs_{ikm} \\ & - \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{s=1}^{S}\sum_{k=1}^{K} \tau_{ij} xt_{ijskm} \Bigg] - \sum_{j=1}^{J}\sum_{s=1}^{S}\sum_{ft=1}^{FT} TAFC_{s,ft} \beta_{js} \Bigg\} * PVAF \end{aligned} \tag{4.1}$$

Including the Tembo's augmented model resulted in the following objective function:

$$\begin{aligned}\max_{q,x,xt,xs,A}\quad NPW = \Bigg\{ \sum_{m=1}^{M} \Bigg[ & \sum_{j=1}^{J}\sum_{s=1}^{S}\sum_{g=1}^{G} \rho_g q_{jsgm} - \sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{f=1}^{F} \alpha_k A_{ikfm} - \sum_{i=1}^{I}\sum_{k=1}^{K} \gamma_k xsp_{ikm} \\ & - \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{s=1}^{S}\sum_{k=1}^{K} \tau_{ij} xt_{ijskm} - \sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{f=1}^{F} \psi_k x_{ikfm} \Bigg] \\ & - \sum_{j=1}^{J}\sum_{s=1}^{S}\sum_{ft=1}^{FT} TAFC_{s,ft} \beta_{js} - \omega HU \Bigg\} * PVAF \end{aligned} , \tag{4.2}$$

For each plant location and size, total fixed costs, *TAFC*, are charged to the objective function only if the corresponding binary variable attains a value of one. *TAFC* is defined as

$$TAFC_{s,ft} = AFC_{s,ft} + OMA_{s,ft}, \tag{4.3}$$

where $AFC_{s,ft}$ is annual fixed charge amortized over the life of the plant and when the facility is type *ft*. $OMA_{s,ft}$ is annual operating and maintenance cost, assumed to be a fixed proportion of $AFC_{s,ft}$. In this study, $OMA_{s,ft}$ is assumed to be equal to two percent and five percent of $AFC_{s,ft}$ for *ft* = "storage" and *ft* = "process", respectively. The expected life of the plant is fifteen years. If we assume that all years are identical, the annual net benefits can be treated as an annuity. The above model uses this assumption and defines the *NPW* with the present value of an annuity factor (*PVAF*). Hence, *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. The simplification implied by assuming that the years are identical is necessary as a check on dimensionality, without much loss of generality (Tembo).

Notice that in Tembo's model (equation 4.1) the third set of summation signs are summing $\alpha_{kh} * A_{ikfhm}$ over *i*, *k*, *f*, and *h*, and $\alpha$, the cost of producing biomass, is defined as:

$$\alpha_{kh} = HC_{kh} + \sum_{bc=1}^{BC} POC_{k,bc} + NCOST_k \qquad \forall k, h, \tag{4.4}$$

where $HC_{kh}$ is the cost of harvesting a unit of biomass *k* using harvest structure *h* (either farm structure or integrate structure), $POC_{k,bc}$ is the cost associated with establishment, maintenance, land rent and procurement (opportunity cost) of biomass of species *k*, and $NCOST_k$ is the cost of nitrogen fertilizer used in the production of biomass *k*. The subscript *bc* = {Establishment costs, Maintenance costs, Land rent, Opportunity cost of biomass}, refer to Table 20 in Appendix A. *A* is defined as the acres of biomass harvested using harvest structure *h*. On the other hand, in the model with harvest unit as an integer activity (equation 4.2) the third set of summation signs are summing $\alpha_k * A_{ikfm}$ over *i*, *k*, and *f*. This formulation does not include the harvest structure subscript, *h*, as a fixed charge since total harvest capacity, harvest unit, and cost of harvesting are calculated endogenously in the model. In this case the definition of $\alpha$ changes, that is,

$$\alpha_k = \sum_{bc=1}^{BC} POC_{k,bc} + NCOST_k \qquad \forall k. \tag{4.5}$$

Notice that $HC_{kh}$ is not included in equation 4.5 as is the case with equation 4.4. Also the definition of $POC_{k,bc}$ is the cost associated with establishment, maintenance and land rent of biomass of species *k*, and $NCOST_k$ is as defined above. $POC_{k,bc}$ does not include procurement (opportunity cost) of biomass of species *k* because biomass is either purchased per ton or land rent per acre is paid. Land rent per acre is assessed only for biomass species grown on CRP land since their purchase cost is assumed zero. In order to avoid confusion with the way the government pays farmers for CRP land, it was assumed that the biomass gasification industry would continue to pay for LCB harvested on CRP land on per acre basis. Therefore in equation (4.5), $POC_{k,bc}$ takes land rent values of zero for biomass not grown on CRP land since these grasses are assessed a purchase cost per ton, $\psi_k$ in equation 4.2. On the contrary, biomass grown on CRP land takes on positive values for land rent per acre since they are assessed a per ton purchase cost of zero. In summary, when land rent is assessed i.e. when *bc* includes positive land rent for a particular biomass species such as biomass species that are grown on CRP land, the vector of purchase prices for biomass species, $\psi_k$, takes on values of zero for those LCB species (see Table 6 in the Data Section).

In Tembo's model (equation 4.1) the fourth set of summation signs are summing $\gamma_k * xs_{ikm}$ over *i*, *k*, and *m*, where $\gamma$ is the storage cost per ton per month. $xs_{ikm}$ is defined in Table 6 above as tons of biomass *k* stored in the field at county *i* in month *m*. Based on this formulation each ton of biomass in storage in a particular month was assessed the storage charge. This means if a certain quantity of biomass was carried over from the previous month it incurred another storage charge per ton in the present month. This resulted in multiple storage charges incurred for biomass stored. To allow for biomass field storage charges to be assessed only once when biomass goes into storage, in equation (4.2) the variable $xsp_{ikm}$ replaces $xs_{ikm}$ (equation 4.1). $xsp_{ikm}$ is as defined in Table 6 above. And $\gamma_k$ changes in definition to storage cost per ton. This formulation allows the model to assess a storage charge per ton once only when harvested biomass goes into field storage, regardless of how long it stays in storage. In this case no multiple storage charges are incurred over the storage life. Due to this modification to the objective function an additional constraint (equation 4.11) was constructed and added to Tembo's original constraint set.

As noted, in Tembo's model, harvest per month was not constrained. To accommodate the harvest unit integer activity's monthly capacity constraint and eradicate the fixed harvest charge per acre, the following constraints in Tembo's model (i.e. equations 4.6 to 4.10) were modified and additional constraints (equation 4.12, 4.13 and 4.24) were constructed and added to the constraint set as shown below. Equations (4.14) through (4.20) and equations (4.22) and (4.23) are as they were in Tembo's model. In equation (4.21) the model is restricted to solve for one plant in the current formulation. In Tembo's model equation (4.21) was restricted to solve for multiple plants. The net present worth is maximized subject to the following constraints:

The first constraint requires that the harvested acres may not exceed the number of acres in each county that can be harvested for biorefinery biomass feedstock. $BP$ as defined is the proportion of land in acres that can be harvested for biomass feedstock. $BP$ includes $BIPROP$ and $CBIPROP$, which represent the proportion of harvestable acres not enrolled in CRP and those enrolled in CRP, respectively. In this model $BIPROP$ is assumed to be 10% of acres in each county and *CBIPROP* is assumed to be 25% of CRP acres in each county.

$$\sum_{f=1}^{F}\sum_{m=1}^{M} A_{ikfm} - \sum_{l=1}^{L} BP_{ikl} LAND_{ikl} \le 0, \qquad \forall i,k. \tag{4.6}$$

The second constraint ensures that biomass harvested is equal to the available biomass in the field less any field losses. The yield adjustment factor, *YAD*, is based on the assumption that biomass yields depend upon harvest month. *BYLD* is as defined above. In this model formulation it is assumed that all biomass feedstock is harvested from the proportion of harvestable acres.

$$\sum_{f=1}^{F} x_{ikfm} - YAD_{km} \sum_{f=1}^{F} A_{ikfm} BYLD_{ikf} = 0, \qquad \forall i,k,m. \tag{4.7}$$

The following constraint states that no acres may be harvested during months in which the yield adjustment factor is equal to zero. *YAD* varies from zero to one depending on the month the biomass is harvested (refer to Table 8 in the Data Section). The yield adjustment factor, *YAD*, is based on the assumption that biomass yields are highest if harvested at certain times of the year and decline thereafter. The yield adjustment factor permits tradeoff between in-field losses and in-storage losses.

$$\sum_{f=1}^{F} A_{ikfm} = 0 \qquad \text{if } YAD_{km} = 0, \qquad \forall i,k,m. \tag{4.8}$$

The following constraint states that in each month and at each source, the sum of biomass shipped to plants and biomass put in storage of each biomass type, *k*, should equal the sum of current production and usable portion of stored biomass.

$$\sum_{j=1}^{J}\sum_{s=1}^{S} xt_{ijskm} + xs_{ikm} - \theta_{ik} xs_{ikm-1} - \sum_{f=1}^{F} x_{ikfm} = 0, \qquad \forall i,k,m. \tag{4.9}$$

This constraint ensures that quantity of biomass shipped out plus that lost in in-field storage balance with total biomass harvested.

$$(4.10) \qquad \sum_{f=1}^{F}\sum_{m=1}^{M} x_{ikfm} - \sum_{j=1}^{J}\sum_{s=1}^{S}\sum_{m=1}^{M} xt_{ijskm} - (1-\theta_{ik})\sum_{m=1}^{M} xs_{ikm} = 0, \quad \forall i,k.$$

The following constraint states that, in each month, the quantity of biomass harvested plus that quantity removed from storage must equal the quantity of biomass transported from biomass producing counties to biorefineries plus that quantity placed in storage. In other words the equation says total supply should equal total demand.

$$(4.11) \qquad \sum_{i=1}^{I}\sum_{k=1}^{K}(x_{ikm} + xsn_{ikm}) - \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{s=1}^{S}\sum_{k=1}^{K} xt_{ijskm} - \sum_{i=1}^{I}\sum_{k=1}^{K} xsp_{ikm} = 0, \quad \forall m.$$

The next constraint states that the sum of harvest units used in each month may not exceed the total number of harvest units endogenously determined by the model.

$$(4.12) \qquad \sum_{i=1}^{I} xhu_{im} - HU \leq 0, \quad \forall m.$$

The next constraint states that, in each biomass producing county and month, the quantity of biomass harvested may not exceed the combined harvesting capacity of the number of harvest units determined by the model.

$$(4.13) \qquad \sum_{k=1}^{K} x_{ikm} - xhu_{im} CAPHU_{im} \leq 0, \quad \forall i,m.$$

The following capacity constraint links biomass processing capacity at the plant to the binary variable. If $\beta_{js} = 1$, $CAPP_s \beta_{js} = CAPP_s$, the processing capacity upper bound in units of bio-products, and the total production at each plant in that month will be bounded by $0 \leq q_{jsem} \leq CAPP_s$. If $\beta_{js} = 0$, expression $CAPP_s \beta_{js}$ will also equal to zero and since $q_{jsem}$ cannot assume negative value, then it must also equal zero.

$$q_{jsem} - CAPP_s \beta_{js} \leq 0, \qquad \forall j, s, m. \tag{4.14}$$

The next constraint links biomass storage capacity at the plant to the binary variable. If $\beta_{js} = 1,\ CAPS_s \beta_{js} = CAPS_s,$ the total biomass storage at any plant will be bounded by $0 \leq xs_{jkm} \leq CAPS_s$. If $\beta_{js} = 0,$ expression $CAPS_s \beta_{js}$ will also equal to zero and since $xs_{jkm}$ cannot assume negative value, then it must also equal zero. No storage upper-bounds are assumed for in-field storage.

$$\sum_{k=1}^{K} xs_{jkm} - CAPS_s \beta_{js} \leq 0, \qquad \forall j, s, m. \tag{4.15}$$

The next equation imposes the constraint that total biomass processed or stored at the plant may not exceed the total biomass supply.

$$\sum_{i=1}^{I} xt_{ijskm} + \phi_{jk} xs_{jkm-1} - xs_{jkm} - xp_{jskm} = 0, \qquad \forall j, k, m, s. \tag{4.16}$$

The next equation balances total biomass delivered to the plant with the sum of processed biomass and on-site storage losses.

$$\sum_{i=1}^{I} \sum_{m=1}^{M} xt_{ijskm} - (1 - \phi_{jk}) \sum_{m=1}^{M} xs_{jskm} - \sum_{m=1}^{M} xp_{jskm} = 0, \quad \forall j, k, s. \tag{4.17}$$

This following constraint allows imposition of minimum biomass inventory at the plant. To avoid biomass supply disruptions, the model allows imposition of minimum biomass inventory through equation (4.18). In all the runs made in this study, as in Tembo's model, minimum inventory was set equal to zero, by assumption.

$$\sum_{k=1}^{K} xs_{jkm} - MBINV_s \beta_{js} \geq 0, \qquad \forall j, m, s. \tag{4.18}$$

This next constraint assumes a Leontief production function at the processing facility. If we assume a Leontief production function at the processing facility (fixed input-output coefficients), the quantity of each output produced should be directly equal to the product of the corresponding transformation coefficient, $\lambda$, and quantity of biomass used, $xp$ (summed over all biomass types). The inequality gives allowance for production losses.

$$q_{jsgm} - \sum_{k=1}^{K} \lambda_{kg} xp_{jskm} \le 0, \qquad \forall g, j, m, s. \tag{4.19}$$

The following constraint imposes a Leontief production function possibilities frontier between the bioproduct and each by-product. This condition ensures that any production of the bioproduct results in the corresponding amount of the by-products (externalities). For the runs in this study, as in Tembo's model, $\lambda$ is assumed to be zero for all byproducts. This assumption is based on the zero carbon balance argument for the process ($CO_2$) and lack of data regarding byproducts.

$$q_{jsem}\lambda_{kg} - q_{jsgm}\lambda_{ke} = 0, \qquad \forall g, j, k, m, s. \tag{4.20}$$

The constraint below represents an upper bound on the number of plants that can be built, assumed here to be equal to one. It is understandable that if a particular plant is too small this constraint will force the model to construct a larger plant other than construct several smaller-sized plants at one location.

$$\sum_{j=1}^{J} \sum_{s=1}^{S} \beta_{js} \le 1. \tag{4.21}$$

These constraints are the non-negativity conditions. The equation constrains the model from negative quantities of the choice variables.

$$A_{ikfm}, x_{ikm}, xs_{ikm}, xs_{jkm}, xt_{ijskm}, xp_{jskm}, q_{jsgm} \ge 0. \tag{4.22}$$

The following constraint restricts values of the binary variable to the set of zero and one.

$$(4.23) \qquad \beta_{js} \in \{0,1\}.$$

Finally, the last constraint restricts the number of the harvest units to non-continuous values.

(4.24) $HU$ is a nonnegative integer variable.

The land upper bound in equation (4.6) depends on assumptions about land availability. Two versions of the above model can be derived by alternative definitions of *LAND*. That is,

$$(4.25) \quad LAND_{ikl} = \begin{cases} BIPROP * CURACRE + \\ CBIPROP * CCURACRE, & \text{if existing biomass acreage is used} \\ \\ BIPROP * POTACRE, & \text{if model permits displacement of other} \\ & \text{activities,} \end{cases}$$

where *CURACRE*, *CCURACRE* and *POTACRE* are existing biomass acreage other than that on CRP land, existing biomass acreage on land enrolled in CRP and potential acreage, respectively.

The parameter $BIPROP$ represents the proportion of land, not enrolled in CRP, used to produce biomass feedstock for biorefinery processing. $CBIPROP$ represents the proportion of land that is enrolled in CRP used for biomass feedstock production for biorefinery use. Following Kaylen et al. this model, as in Tembo's model, uses 10 percent for $BIPROP$. $CBIPROP$ is assumed to be 25%. According to the 2002 Farm Bill, harvesting of biomass on land enrolled in CRP can only be done once in three years. This means that to supply biomass feedstock to a biorefinery every year 33% of the land can be harvested in any year through rotation. Consequently, a conservative rate of 25% was chosen in this study as a proportion of harvested CRP land. The alternative specification of the land upper bound (Equation 4.25), i.e. $BIPROP * POTACRE$, is used only when switchgrass is permitted to displace some of the existing cropping activities.

The eleven prospective facility locations (counties) used in the model were selected on the basis mainly of concentration of biomass production and availability of road infrastructure (Tembo). If a particular location is optimal, both processing and onsite biomass storage facilities need to be constructed. Each optimal plant is subject to monthly processing, *CAPP*, and storage, *CAPS*, capacities. Choice of optimum plant size from among three options, $s$ = {small, medium, large}, is influenced to a great extent by size economies. The subscript $e$ refers to ethanol, where $e \subset g$.

Given some base values of all parameters, the above model determines a base solution by maximizing the objective function equation (4.2), subject to the constraint equations (4.6) through (4.24).

To determine how the method of modeling harvest and procurement cost changes the cost to deliver a ton of LCB, the results of the model with harvest units, equation (4.2), are compared to those of a model that assumes a harvest cost charged as a parameter on per ton basis. This alternative model is presented below (equation 4.26).

Maximize Net Present Worth:

$$\max_{q,x,xt,xs,A} \; NPW = \left\{ \sum_{m=1}^{M} \left[ \sum_{j=1}^{J}\sum_{s=1}^{S}\sum_{g=1}^{G} \rho_g q_{jsgm} - \sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{f=1}^{F} \alpha_k A_{ikfm} - \sum_{i=1}^{I}\sum_{k=1}^{K} \gamma_k xsp_{ikm} \right.\right.$$

$$\left. - \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{s=1}^{S}\sum_{k=1}^{K} \tau_{ij} xt_{ijskm} - \sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{f=1}^{F} \psi_k x_{ikfm} \right] \tag{4.26}$$

$$\left. - \sum_{j=1}^{J}\sum_{s=1}^{S}\sum_{ft=1}^{FT} TAFC_{s,ft}\beta_{js} - \sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{f=1}^{F} \kappa x_{ikfm} \right\} * PVAF$$

Equation 4.26 is maximized subject to equations 4.6 through 4.23 minus equations 4.12 and 4.13.

In addition to changes in model assumptions and formulation, the present study differs from Tembo's in terms of model application. Tembo's model enables the harvest of wheat straw, corn stover, old world bluestem, native tall prairie grasses, native mixed prairie grasses, native short prairie grasses, bermudagrass, and tall fescue from Oklahoma farm and ranch land on which these species are currently being produced. His model also enables the leasing of cropland for production of switchgrass. For the proposed research the revised model will also be solved for a subset of the species. For example, the model may be solved assuming that only wheat straw and corn stover would be available or biomass would only be harvested from CRP land.

## The Crop Residue Mixed Integer Mathematical Programming Model

The second objective in this study may be achieved by redefining the subscript *k* in all the equations to include only two LCB feedstock species i.e. wheat straw and corn stover. As defined above subscript $k = \{1, 2,\ldots, K\}$ includes nine LCB sources: wheat straw, corn stover, old world bluestem, tall native prairies, short native prairies, mixed native prairies, improved bermudagrass, tall fescue grass, and switchgrass. By redefining the set of LCB feedstock species, *k*, it will include only agricultural residues (i.e. wheat straw and corn stover). Below is the mixed integer mathematical programming model for analyzing the second objective.

Maximize Net Present Worth:

$$\underset{q,x,xt,xs,A}{\text{Max}} \quad NPW = \left\{ \sum_{m=1}^{M} \left[ \sum_{j=1}^{J}\sum_{s=1}^{S}\sum_{g=1}^{G} \rho_g q_{jsgm} - \sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{f=1}^{F} \alpha_k A_{ikfm} - \sum_{i=1}^{I}\sum_{k=1}^{K} \gamma_k xsp_{ikm} \right.\right.$$

$$\left. - \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{s=1}^{S}\sum_{k=1}^{K} \tau_{ij} xt_{ijskm} - \sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{f=1}^{F} \psi_k x_{ikfm} \right] \tag{4.27}$$

$$\left. - \sum_{j=1}^{J}\sum_{s=1}^{S}\sum_{ft=1}^{FT} TAFC_{s,ft} \beta_{js} - \omega HU \right\} * PVAF$$

The net present worth is maximized subject to equations 4.6 through 4.24. In this model formulation modifications are done to the definitions of the first two constraints i.e. equations 4.6 and 4.7. The variable *BP* in the constraint equation 4.6 is defined somewhat differently. As stated above *BP* includes *BIPROP* and *CBIPROP* , which represent the proportion of harvestable acres not enrolled in CRP and those enrolled in CRP, respectively. Since this model includes crop residues only as biorefinery feedstock hence *BP* in this formulation is equal to *BIPROP* . It does not include *CBIPROP* . In this model formulation *BIPROP* is defined as harvestable acres of crop residues and is assumed to be 100% of acres under crop residues in each county. In other words, in the crop residue model it is assumed that all acres under crop residues are harvestable.

The second modification involves the definition of *BYLD* in the second constraint (equation 4.7). *BYLD* was defined above as the yield of biomass in each county. In this model formulation *BYLD* is defined as 60% of the yield of crop residues in dry tons per acre. It is assumed that only 60% of the biomass feedstock is harvestable from all the available acres under crop residues leaving 40% for soil erosion control and enhancement of soil fertility. All other constraints are as defined above (i.e. equations 4.8 through 4.24).

## The CRP Mixed Integer Mathematical Programming Model

To achieve the third objective subscript *k* may further be redefined to include LCB feedstock grown only on CRP land. The feedstock in this category includes old world blue stem and mixed native prairies. Tembo's model is constructed to permit limiting the proportion of potential acres in a county that may be used for production of biomass. The base model assumes that this proportion is 10 percent, following Kaylen et al.'s conservative specification. In this model formulation the proportion of potential Based on the 2002 farm bill CRP acres that may be used for harvesting of LCB feedstock is assumed to be 25%. The objective function for analyzing objective three, which considers a biorefinery that uses biomass grass that grows on CRP land only is given as:

(4.28)

$$\underset{q,x,xt,xs,A}{\text{Max}} \quad NPW = \left\{ \sum_{m=1}^{M} \left[ \sum_{j=1}^{J}\sum_{s=1}^{S}\sum_{g=1}^{G} \rho_g q_{jsgm} - \sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{f=1}^{F} \alpha_k A_{ikfm} - \sum_{i=1}^{I}\sum_{k=1}^{K} \gamma_k xsp_{ikm} - \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{s=1}^{S}\sum_{k=1}^{K} \tau_{ij} xt_{ijskm} \right] - \sum_{j=1}^{J}\sum_{s=1}^{S}\sum_{ft=1}^{FT} TAFC_{s,ft}\beta_{js} - \omega HU \right\} * PVAF$$

The objective function is maximized subject to equations 4.6 through 4.24. However one modification is made to the first constraint (equation 4.6). As in the crop residue model the variable *BP* in the constraint equation 4.6 is also defined differently. In this formulation *BP* is equal to *CBIPROP* , which represents the proportion of harvestable acres enrolled in CRP. It does not include *BIPROP* . Since this is a CRP model only acres enrolled in CRP are included in this model formulation as sources of biorefinery feedstock. *CBIPROP* is assumed to be 25% of CRP acres in each county. All other constraints are as defined above (i.e. equations 4.7 through 4.24).

## Data Sources and Assumptions

### Biomass Production Regions and Potential Plant Locations

For the first two objectives, biomass supply regions include all 77 counties in Oklahoma (Figure 2). For the third objective, biomass supply counties include 52 counties in southern Kansas, the 77 Oklahoma counties and 32 counties in the Texas Panhandle (Figure 3). Counties from Kansas and Texas were added because the quantity of LCB on CRP acres was insufficient for a large plant. When harvesting is limited to 25% of total acres the state of Oklahoma did not have adequate CRP acres to provide required feedstock for a large plant (a plant that can process 4,000 dry tons of LCB per day), therefore additional biomass feedstock were drawn from CRP acres in Kansas and Texas.

Eleven Oklahoma counties were selected as possible locations for the LCB biorefinery plant. The eleven (11) prospective plant locations were selected on the basis of biomass relative density, proximity to the biomass producing counties, and availability of road infrastructure. A city approximately at the center of the county was used to represent the county as a whole. The distance between any biomass supplying county and any plant location was estimated by the distance from the county's representative point (i.e. the centrally located city) to the plant location (Figure 4 shows the map with plant locations). The city-to-city distances reported in the official Oklahoma State road map were used to estimate distances between any cities in Oklahoma. For Kansas and Texas, the online calculations of distances from city-to-city available on the internet (i.e.

expedia.com) were used to estimate distances between biomass supplying counties and the plant location.

The eleven potential plant locations are among the total number of biomass supplying counties. Based on the method used to estimate distances between biomass supply counties and plant location a distance of zero miles would be assumed when a plant is located in a biomass supplying county, which may be misleading. To avoid assuming zero intracounty distances one-half of the longest straight-line distance in each county (radius) were added to the intercounty distance estimates (Tembo).

## Assumptions on Transportation Cost

Total cost of transporting biomass from the biomass supplying counties to the biorefinery plant location was computed using the biomass transportation cost regression equation reported by Bhat, English and Ojo. The authors expressed their equation as follows

$$TRC_{ij} = 34.08 + 0.62 d_{ij}, \tag{4.29}$$

where $d_{ij}$ is the round-trip distance, in kilometers, from biomass producing county $i$ to plant location $j$, and $TRC$ is the transportation cost in U.S. dollars per 15.42 dry metric tons (17 dry tons) truck. Equation (4.29) was estimated based on weekly trucking rates charged by agricultural produce transporters across different U.S. regions and assumes that the herbaceous crops are harvested, baled and transported in form of bales (Bhat, English and Ojo). Tembo converted the distance from kilometers to miles since distances in the model use miles as a unit of measurement. Hence equation (4.29) became, (4.30)

$$TRC_{ij} = 34.08 + 1.00 \delta_{ij},$$

**Figure 2.** Map showing all counties in Oklahoma included in the study

**Figure 3.** **Map showing counties of Oklahoma, Texas Panhandle, and southern Kansas included in the CRP feedstock-only model**

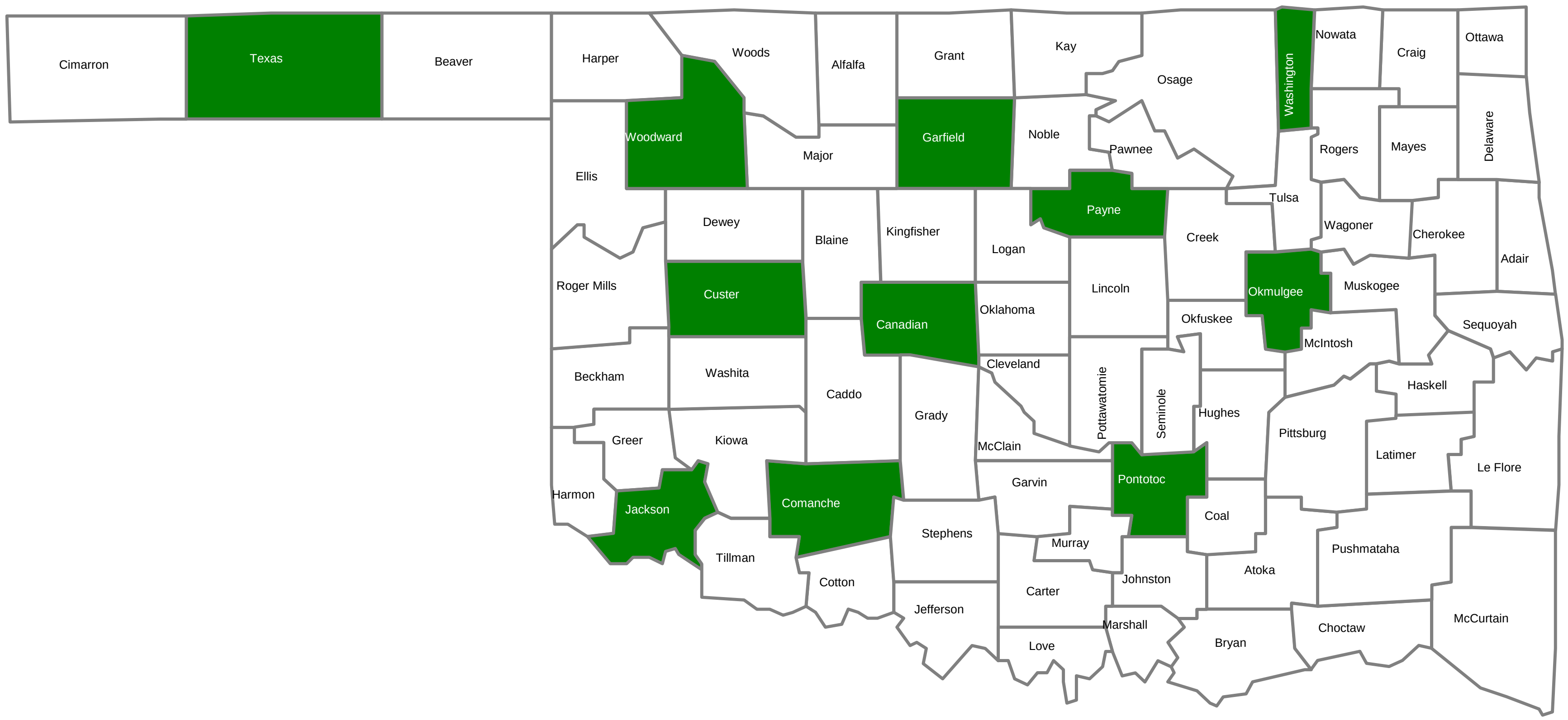


Figure 4. Map showing eleven potential biorefinery locations

where $\delta_{ij} = \frac{d_{ij}}{1.609}$ is the round-trip distance in miles. The average per dry ton transportation cost, $\tau_{ij}$, that is used in the study was determined by dividing equation (4.30) by the assumed truck capacity (17 tons). As Tembo notes this specification makes the transportation rates ($/ton/mile) to vary by round-trip distance. The transportation rates decline nonlinearly with increase in round-trip distance.

## Biomass Production

Unlike most other studies, more than one type of LCB is considered in this study. For the first objective a variety of LCB such as corn stover, wheat straw, tall native prairie grasses, short native prairie grasses, mixed native prairie grasses, old world blue stem, bermuda grass, tall fescue grass and switchgrass are considered as feedstock for the biorefinery. To analyze the second objective the study uses crop residues only, thus corn stover and wheat straw. To analyze the third objective, the model includes biomass feedstock grown on CRP land, thus mixed native prairie grasses and old world blue stem. Tembo, Epplin, and Huhnke, noted that the state of Oklahoma has a variety of potential LCB feedstock, including plant residues, indigenous native prairies, and improved pastures. In addition, cropland could be used to produce dedicated feedstock crops such as switchgrass. Switchgrass is considered in this scenario due to its high-yielding nature, secondly switchgrass is native to North America, hence well adapted to the local climate.

In Oklahoma crop residues such as 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. In Oklahoma, perennial grasses such as switchgrass may be permitted to mature in the field and be harvested as late as February of the following year. Therefore utilizing a variety of feedstock enables an extended harvest system from June through February of the following year.

Five-year data (1999-2003) from the Oklahoma Agricultural Statistics (Oklahoma Department of Agriculture) were used to estimate the average number of acres and yields of corn and wheat for each of the Oklahoma counties. The reported yields in these data sets pertain to corn and wheat grain, not their biomass residues. As is in Tembo's model, this study also computes the corresponding yields of crop residues using regression equations reported by Steiner, Schomberg and Morrison. For corn, the estimated equation relating grain yield to stover yield is

$$CSY = 3308.2 + 0.5086CGY\ , \tag{4.31}$$

where $CSY$ and $CGY$ are corn stover yields and corn grain yields, respectively. Similarly, the equation relating wheat grain yield to wheat straw yield is given as

$$WSY = 329.99 + 1.5573WGY\ , \tag{4.32}$$

where $WSY$ and $WGY$ are wheat straw yields and wheat grain yields, respectively. In both equations (4.31) and (4.32), both residue and grain yield estimates are in pounds per acre. In terms of the notation of the above model, crop residue yields can be defined as

$$BYLD_{i,cr,f} = \begin{cases} CSY_{if}\,, & \text{if } cr = \text{corn stover} \\ WSY_{if}\,, & \text{if } cr = \text{wheat straw,} \end{cases} \tag{4.33}$$

where $cr \subset k$ is a set of crop residues considered where $i$ and $f$ are as defined above. Refer to Figures 5 and 6, which show the distribution of acres and total production, respectively, of crop residues in the biomass producing counties of Oklahoma. In analyzing the first objective it is assumed that 10% of the acres in each county would be

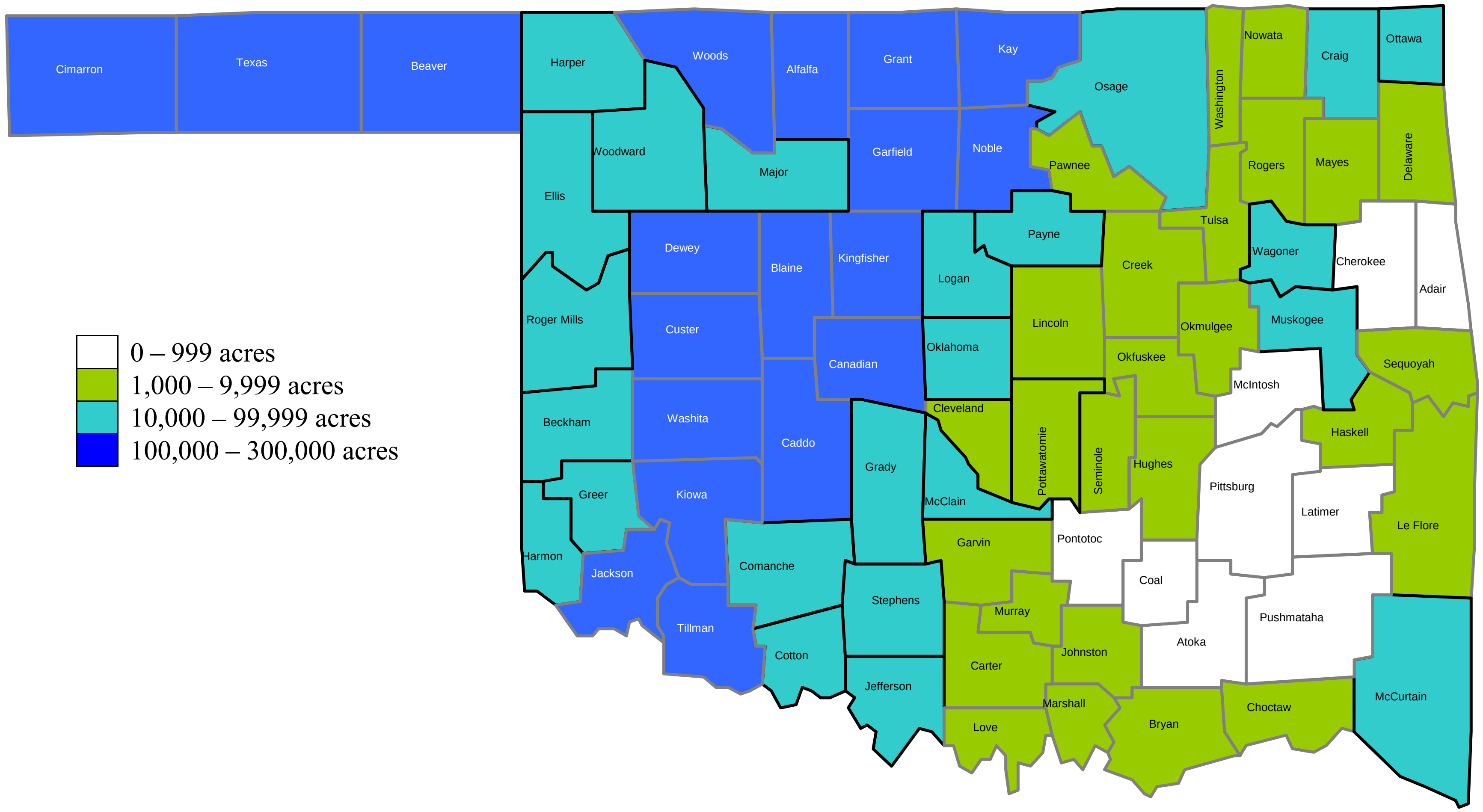


**Figure 5. Map showing the distribution of acres of crop residues in Oklahoma**

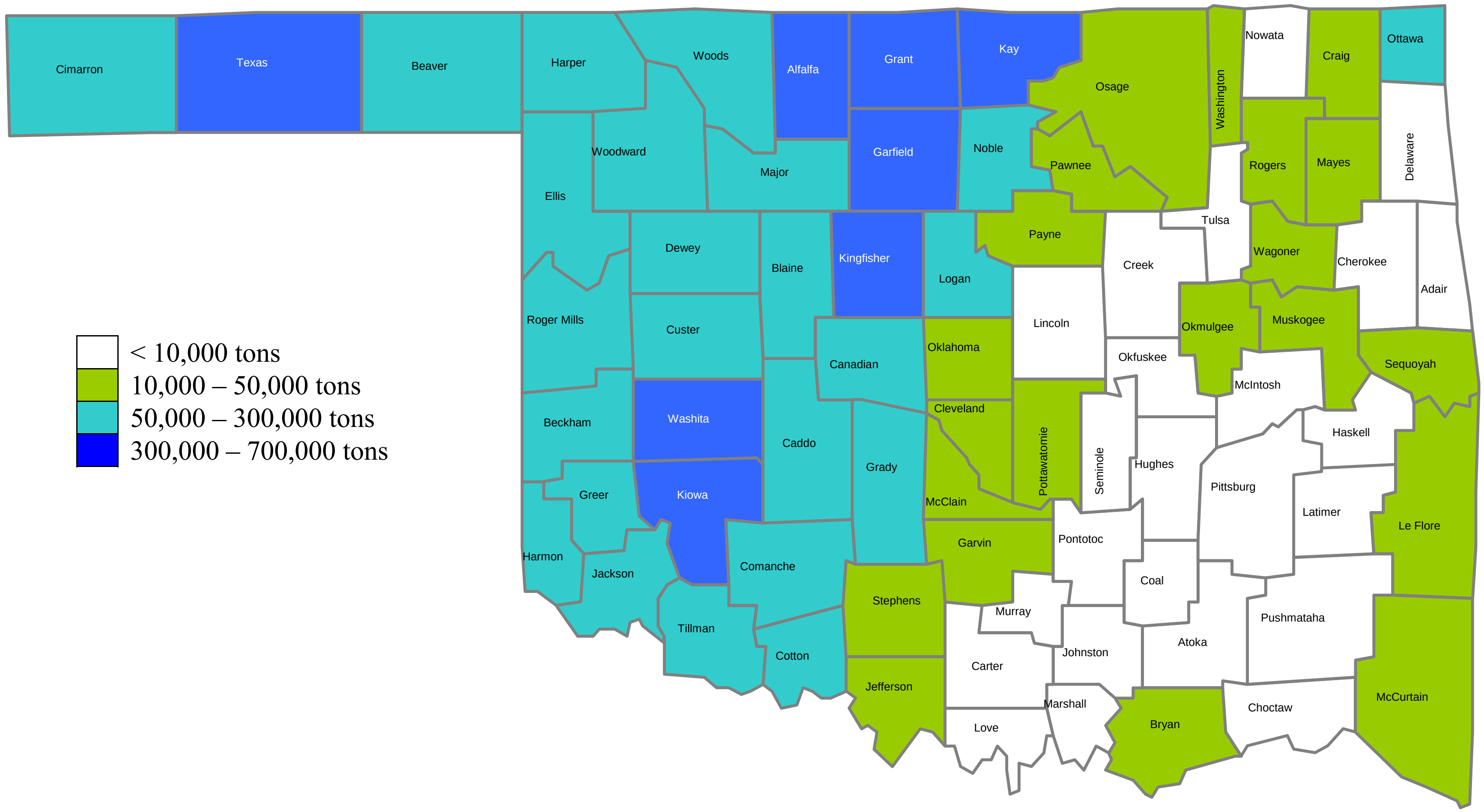


**Figure 6. Map of Oklahoma showing the distribution of yields of crop residues**

harvested. Implicitly, this assumes harvesting all biomass tons on the 10% harvestable acres. On the other hand, in analyzing the second objective it is assumed that 100% of the acres with crop residues would be harvested, but only 60% of the tons of crop residues on each acre would actually be harvested to comply with USDA requirements. The USDA requires that at least 30% of crop residues should be left on the land to avoid serious soil erosion and loss of humus.

In Oklahoma, agricultural land can be categorized into cropland, improved pasture land, native pasture land, rangeland, and CRP land. Estimates of land area under each of these categories, except CRP land, were obtained from the 2002 Census of Agriculture (Bureau of the Census). In general, while native prairies grow on native pastureland and rangeland, improved pasture can only be grown on improved pasture land. Since there was no additional information available through this source that allocated these aggregate figures of broad land categories to the various grasses (i.e. native prairies, improved pastures), Tembo sought expert opinion from the Oklahoma State University's Department of Plant and Soil Sciences (Taliaferro, 2000) to confirm the estimated land proportions for each of the biomass type in each biomass producing region.

CRP acres in this study were based upon 2004 enrollment (USDA, 2004). The Farm Services Agency (Wanger) provided the proportions of acres allocated to the two biomass types grown on CRP land. Table 4 presents the proportions of acres under native prairies, improved pastures and all grasses on CRP land and the corresponding land area under each of the grasses by region in Oklahoma. In this study regions of Oklahoma are defined as Panhandle, Northwest, Southwest, Northeast and Southeast. These regional level proportions were applied to each of the counties in the corresponding region. Biomass

**Table 4. Land Area (in '000 acres) and Proportion of Land Area under Each of Oklahoma's Forage Species by Land-Use Classification**

| Region/Acres/ Proportion | CRP[a] |  | Native Prairies |  |  | Improved Pastures |  |  |  |
|---|---|---|---|---|---|---|---|---|---|
|  | OWB[b] | Mixed Grass | Tall Grass | Mixed Grass | Short Grass | Bermudagrass | OWB[b] | Tall Fescue | Other |
| PANHANDLE |  |  |  |  |  |  |  |  |  |
| Acres | 386 | 129 | xxx[c] | xxx | 1,676 | xxx | 117 | 12 | 37 |
| Proportion | 0.75 | 0.25 | 0.00 | 0.00 | 1.00 | 0.00 | 0.71 | 0.07 | 0.22 |
| NORTHWEST |  |  |  |  |  |  |  |  |  |
| Acres | 194 | 104 | 416 | 3,121 | 624 | 418 | 373 | 11 | 328 |
| Proportion | 0.65 | 0.35 | 0.10 | 0.75 | 0.15 | 0.37 | 0.33 | 0.01 | 0.29 |
| NORTHEAST |  |  |  |  |  |  |  |  |  |
| Acres | 7 | 4 | 3,375 | 178 | xxx | 529 | 11 | 444 | 74 |
| Proportion | 0.65 | 0.35 | 0.95 | 0.05 | 0.00 | 0.50 | 0.01 | 0.42 | 0.07 |
| SOUTHWEST |  |  |  |  |  |  |  |  |  |
| Acres | 136 | 73 | 1,380 | 1,725 | 345 | 589 | 329 | 14 | 439 |
| Proportion | 0.65 | 0.35 | 0.40 | 0.50 | 0.10 | 0.43 | 0.24 | 0.01 | 0.32 |
| SOUTHEAST |  |  |  |  |  |  |  |  |  |
| Acres | 5 | 2 | 2,186 | 243 | xxx | 808 | 11 | 225 | 79 |
| Proportion | 0.65 | 0.35 | 0.90 | 0.10 | 0.00 | 0.72 | 0.01 | 0.20 | 0.07 |

[a] Conservation Reserve Program (CRP)

[b] Old World Bluestem (OWBS)

[c] No production of the feedstock

Sources: Proportions from Taliaferro (1998) and Wanger (2005). Adapted from Tembo (2000)

Total acres per land category (except CRP) from 2002 Census of Agriculture (Bureau of Census)

CRP acres were obtained from 2004 enrolment feedstock grown on the CRP land includes old world bluestem and native prairies grown in mixed stand.

Switchgrass, the only dedicated energy crop considered in this study, is not reflected in Table 4 because the table presents land on which grass is already established. Switchgrass can come into the model solution only if the model finds it optimal to reallocate some of the existing cropland to switchgrass. Table 4 combined with the wheat and corn acres in cropland constitute the current acreage upper bound. If all the various land categories can be reallocated, then potential acreage becomes the land upper bound. The upper bounds may be adjusted so that only a fixed proportion of the land area can be allocated to LCB production (Equations 4.6 and 4.25).

Table 5 gives the CRP land allocations for old world bluestem and mixed native prairie grasses for Southern Kansas and the Texas Panhandle. Biomass yield estimates for old world blue stem and mixed prairie grasses produced on CRP acres were obtained from a survey of biomass yields reported by Sala et al. Figures 7 and 8 give the distribution of CRP acres and biomass production in tons per year.

Since the 2002 Farm Bill stated that CRP land could be harvested only once in three years, meaning only 33% of the land could be harvested, this study assumed that no more than 25% of the CRP land could be harvested in a representative year. Use of other feedstock, in the base model only, was limited to no more than 10 percent of the available acres by county. The average rental rate for CRP land in the region studied was $35 per acre (USDA, 2004). According to 2002 Farm Bill, if the land is harvested for biorefinery feedstock the rate would be reduced by 25 percent or an average of $9 per acre.

**Table 5. CRP Land Area (in ‘000 acres) and Proportion of the Land Area under Each of Southern Kansas and Texas Panhandle Forage Species**

| | CRP[a] | |
|---|---|---|
| Region/Acres/ Proportion | OWB[b] | Mixed Grass |
| TEXAS PANHANDLE | | |
| Acres | 1,336 | 719 |
| Proportion | 0.65 | 0.35 |
| SOUTHERN KANSAS | | |
| Acres | 1,914 | xxx[c] |
| Proportion | 1.00 | 0.00 |

[a] Conservation Reserve Program (CRP)
[b] Old World Bluestem (OWBS)
[c] No production of the feedstock
Sources: Proportions from Wanger (2005)
Total acres for CRP obtained from 2004 enrolment.

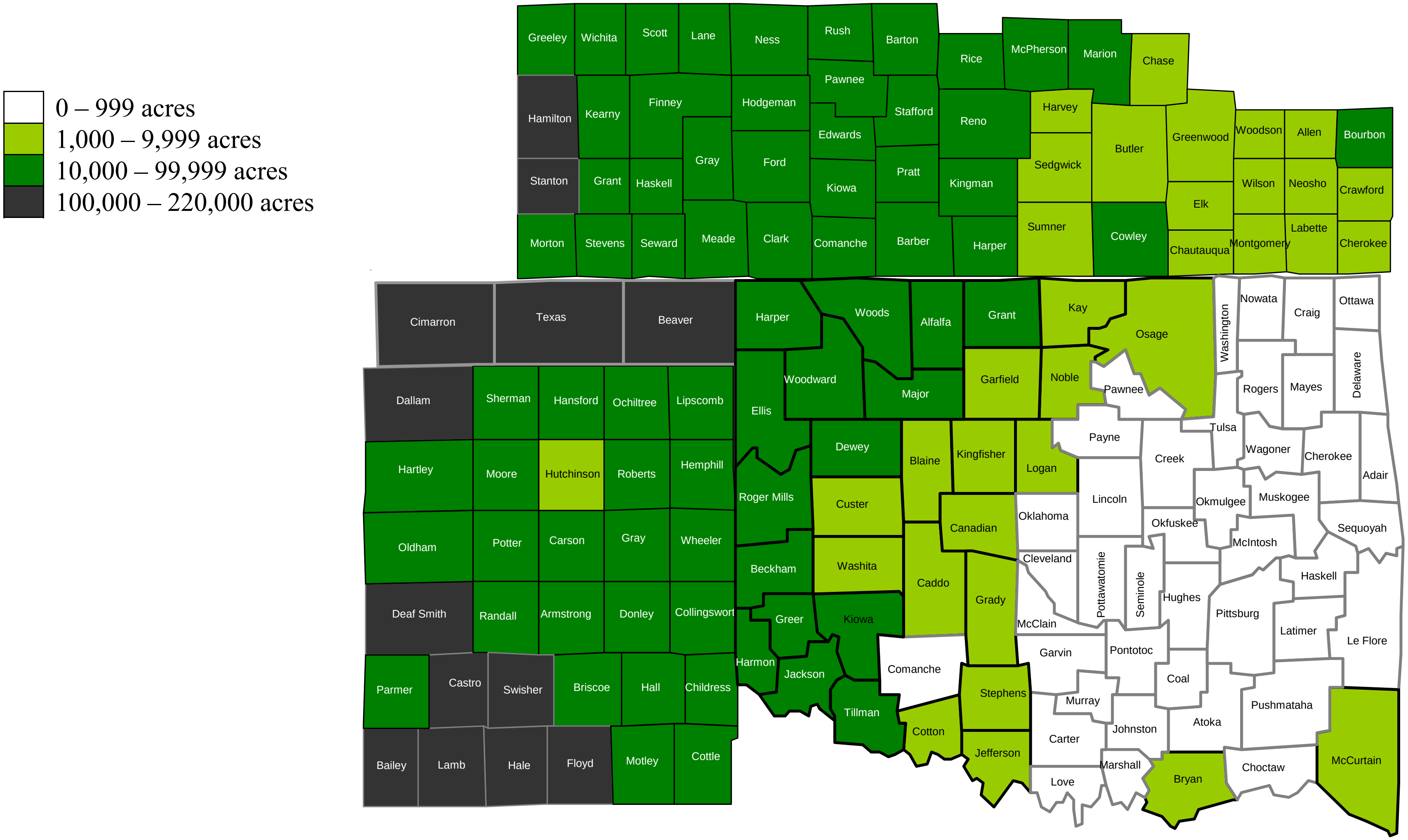


**Figure 7. Map showing acres of biomass on CRP land for counties in southern Kansas, Oklahoma and Texas Panhandle**

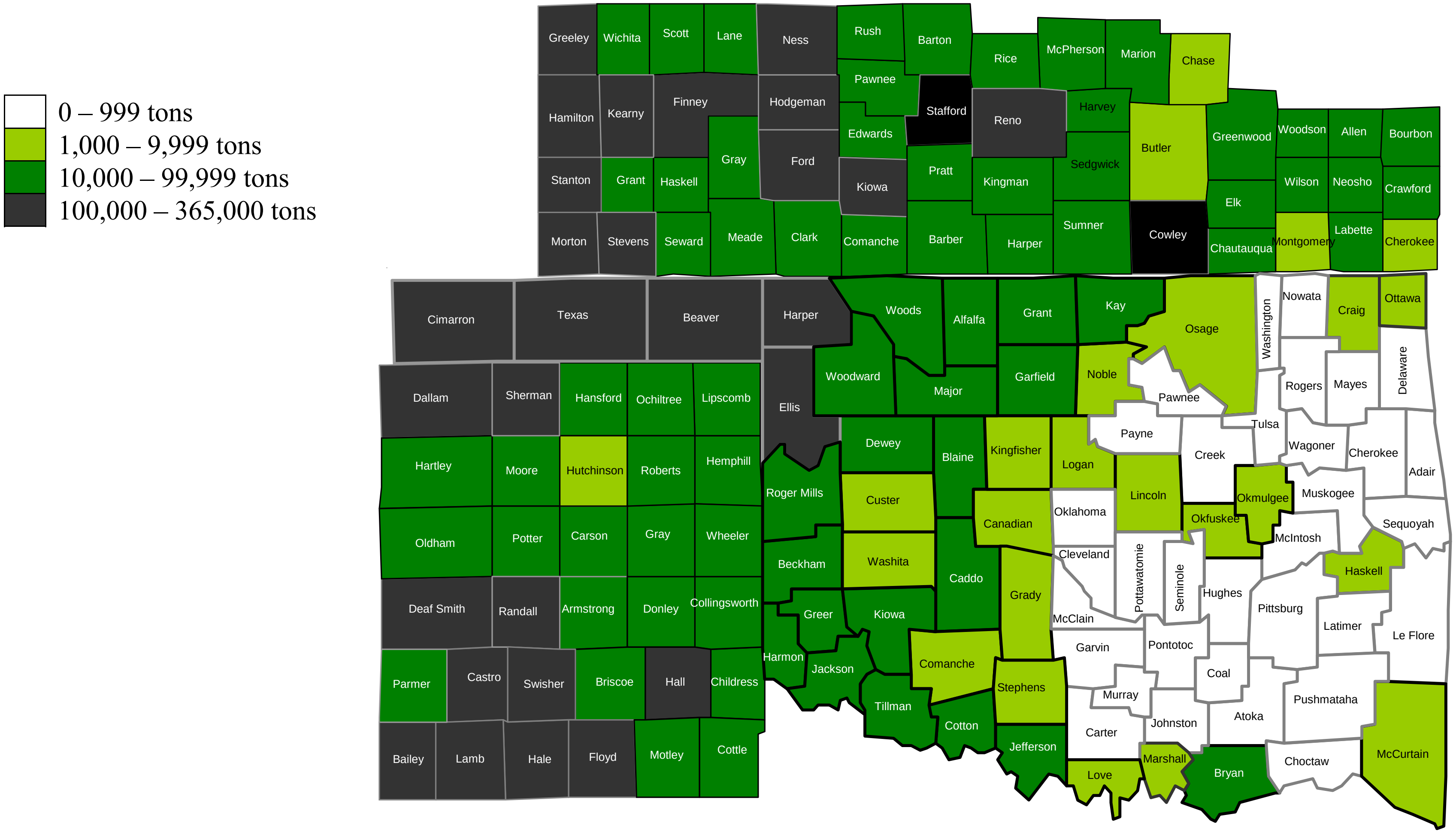


**Figure 8. Map showing production of biomass on CRP land for counties in southern Kansas, Oklahoma and Texas Panhandle**

Consequently, land harvested for biorefinery use was assessed a land rent of $10 per acre in the model to compensate landowners for the reduction in CRP payment and removal of biomass. A charge of $10 per ton was assessed to compensate landowners for removal of all feedstock other than feedstock produced on CRP land ($\psi_k$ in equation 4.2).

Several cost items have to be borne in biomass production and, consequently, in the biorefinery processing of the biomass feedstock. In this study, these costs are categorized as establishment costs, maintenance costs, land rent and biomass purchase cost (all these are included in $\alpha_k$ in equation 4.2). These cost categories vary with different biomass species and a certain cost category may not be applicable to some species. For example, while all grass species (native prairies and improved pasture) and crop residues may be purchased, species of grass that are grown on the CRP land (old world bluestem and mixed native grasses) will be assessed a land rent per acre other than a purchase price per ton (Table 6). In this study production of switchgrass can become a possibility only if the model finds it optimal and establishment costs would be incurred.

Estimates of these cost categories were obtained from Epplin (2004) these costs are presented in Table 6. For the improved pasture and dedicated energy crops, another cost category concerns fertilizer application (maintenance cost in Table 6). In this study, four levels of fertilization are considered for bermudagrass, tall fescue and old world bluestem. These are 50, 100, 150, and 200 pounds of nitrogen per acre per year. The cost of nitrogen fertilizer was assumed to be $0.24 per pound. Estimates of yields corresponding to these fertility levels were obtained through personal consultations with the Oklahoma State University, Department of Plant and Soil Sciences (Taliaferro, 2004). Because no switchgrass yield estimates are available for such multiple fertility regimes,

**Table 6. Biomass Production and Purchase Costs**

| | Cost by Category | | | |
|---|---|---|---|---|
| | Biomass Production Costs ($/acre/year)[a] | | | |
| Feedstock Species | Establishment Costs | Maintenance Costs | Land Rent | Biomass Purchase Cost ($/ton)[a] |
| Wheat Straw | 0.00 | 0.00 | 0.00 | 10.00 |
| Corn Stover | 0.00 | 0.00 | 0.00 | 10.00 |
| Old World Bluestem (CRP)[b] | 0.00 | 0.00 | 10.00 | 0.00 |
| Native Mixed (CRP)[b] | 0.00 | 0.00 | 10.00 | 0.00 |
| Old World Bluestem | 0.00 | 3.00 | 0.00 | 10.00 |
| Native Tall | 0.00 | 0.00 | 0.00 | 10.00 |
| Native Mixed | 0.00 | 0.00 | 0.00 | 10.00 |
| Native Short | 0.00 | 0.00 | 0.00 | 10.00 |
| Bermudagrass | 0.00 | 3.00 | 0.00 | 10.00 |
| Tall Fescue | 0.00 | 3.00 | 0.00 | 10.00 |
| Switchgrass | 11.22 | 3.00 | 0.00 | 10.00 |

[a] Sources: Epplin (2004)
[b] Biomass feedstock that is grown on CRP land. It is assumed that management of grass grown on CRP land differs from the management of the same grass grown as improved pasture.

only one fertility level (75 lb/acre) was used for switchgrass. Potential yield estimates corresponding to this level of nitrogen were obtained from Graham, Allison and Becker. For the native grasses, yield estimates were obtained through a survey of field staff in the respective regions. A zero fertility level is assumed for native prairies and crop residues.

Table 7 summarizes the yield estimates for all the feedstock by region and fertility level, where applicable. The biomass feedstock in this table excludes the feedstock that is grown on CRP land. The county level yield estimates for wheat straw and corn stover were obtained by using the regression equations reported by Steiner, Schomberg and Morrison and data from the Oklahoma Agricultural Statistics. The yields for all other biomass feedstock types are based on regional estimates by field staff. Because the model uses the county as the smallest regional unit, the regional estimates were applied to each of the counties in the respective regions.

In general, biomass yield will be highest if the biomass is harvested in the months before field losses begin. The estimates in Table 7 are potential yield levels assuming that the harvesting is carried out in the months that yield the most for each feedstock. However, harvesting all the biomass in a short period will exert additional pressure and, possibly, increase costs on harvesting and in-field storage. Harvesting cost will increase due to increased required number of harvest machines and crew. Since loss in biomass quantity is also eminent in storage, the decision-maker may wish to tradeoff storage losses with field losses by harvesting later than is appropriate for maximum yield. Figures 9 and 10 give the distribution of acres and production levels of LCB feedstock in Oklahoma, respectively. To develop these maps it was assumed that 150 pounds of nitrogen are applied to the improved pastures and switchgrass.

To allow the model the option of harvesting over a wide range of months, the potential yield (Table 7) is penalized by the yield loss factor corresponding to the month the biomass is actually harvested (Equation 4.7 and 4.8). Table 8 presents the proportions of yields presented in Table 7 that would be attainable in each of the twelve

**Table 7. Dry Biomass Yield Estimates by Region and Fertility Regime**

| | | Yield by Region (tons/acre/year) | | | | |
|---|---|---|---|---|---|---|
| Species | Nitrogen Level (lb) | Oklahoma Panhandle | North-west | South-west | South-east | North-east |
| Bermudagrass | 50 | 1.75 | 1.75 | 1.75 | 2.25 | 1.75 |
| | 100 | 2.50 | 2.50 | 3.00 | 3.50 | 2.50 |
| | 150 | xxx | 3.00 | 3.75 | 4.50 | 3.00 |
| | 200 | xxx | 4.50 | 4.25 | 5.50 | 4.25 |
| Tall fescue | 50 | xxx | xxx | xxx | 1.75 | 2.00 |
| | 100 | xxx | xxx | xxx | 2.25 | 3.00 |
| | 150 | xxx | xxx | xxx | 3.00 | 3.75 |
| | 200 | xxx | xxx | xxx | 3.75 | 4.75 |
| Old world bluestem | 50 | 1.50 | 1.50 | 1.50 | 1.50 | 1.25 |
| | 100 | 2.00 | 2.00 | 2.25 | 2.36 | 2.31 |
| | 150 | 2.50 | 2.50 | 3.00 | 2.75 | 2.75 |
| | 200 | 3.00 | 3.00 | 3.75 | 3.50 | 3.25 |
| Switchgrass | 75 | 0.00 | 5.00 | 5.00 | 6.50 | 6.00 |
| Native prairies | 0 | xxx | 1.57 | 1.40 | 2.09 | 3.00 |
| Native mixed | 0 | xxx | 1.27 | 1.25 | 1.68 | 1.90 |
| Native short | 0 | 0.67 | 0.95 | 0.85 | xxx | Xxx |
| *Wheat straw | 0 | 0.72 | 0.71 | 0.68 | 0.80 | 0.81 |
| *Corn stover | 0 | 3.01 | 2.14 | 2.08 | 2.14 | 2.05 |

xxx The feedstock is not grown in that region
*The values in the table are averages over all counties in each region

Sources: Taliaferro (2004) for bermudagrass, tall fescue and old world bluestem
Survey of county field staff (1998) for the native prairies
Graham, Allison and Becker (1996) for switchgrass
Regression estimates, E(forage yield) = f(grain yield), for crop residue using data from Steiner, Schomberg and Morrison

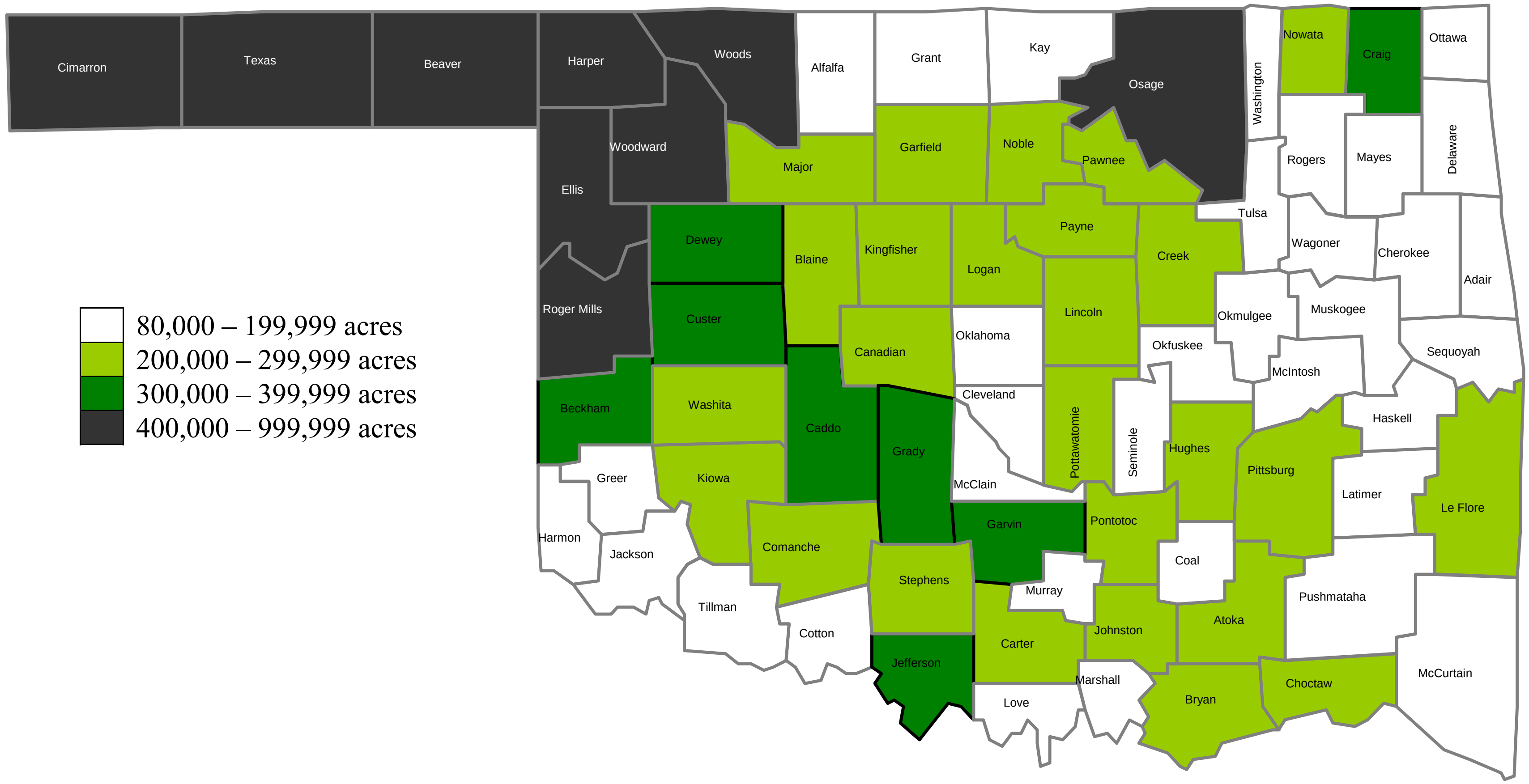


**Figure 9. Map of Oklahoma showing the distribution of acres of LCB in Oklahoma**

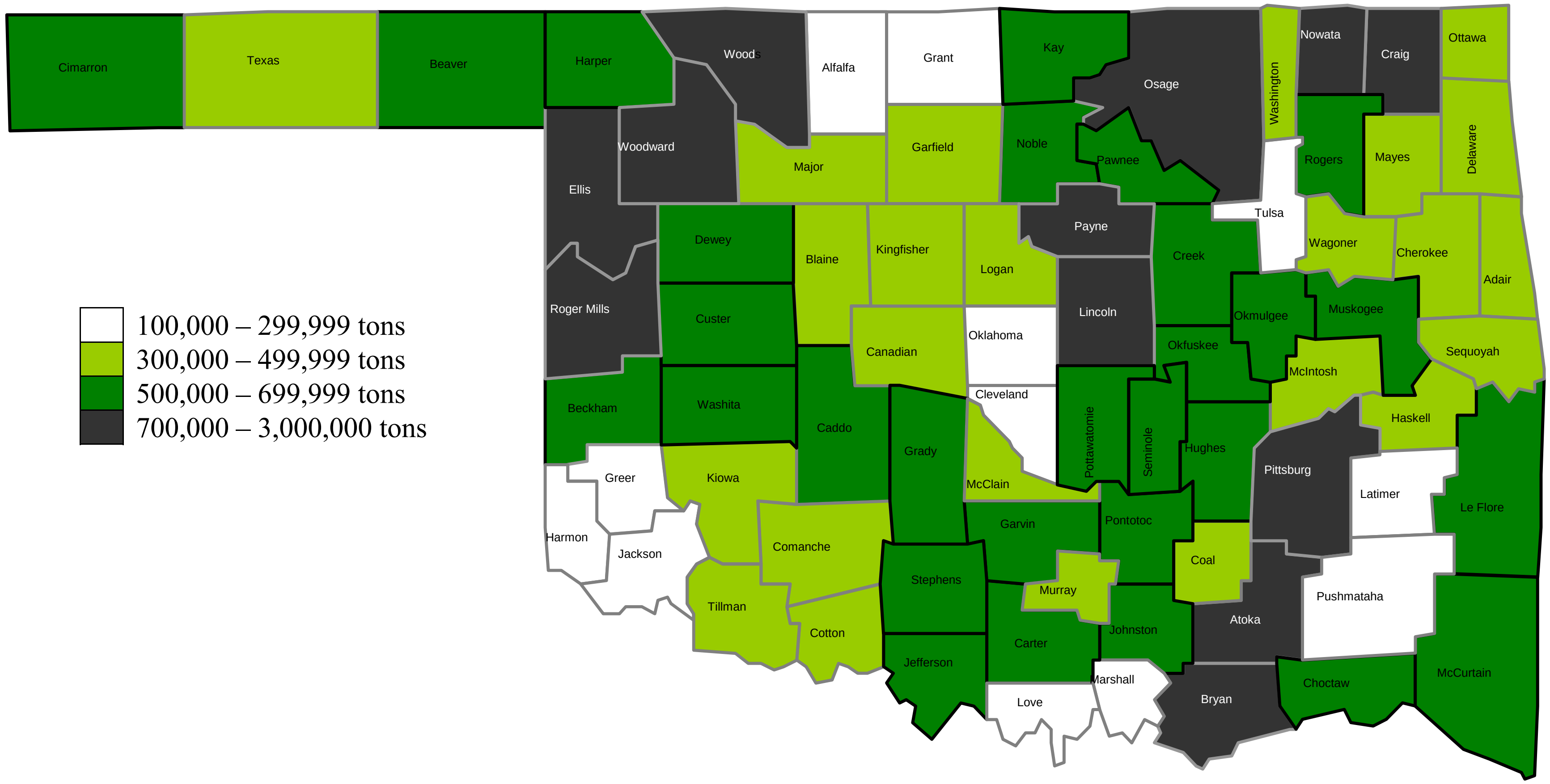


**Figure 10.** Map of Oklahoma showing production of LCB

**Table 8. Yield Adjustment Factor by Month of Harvest**

| | Proportion of Potential Yield by Month of Harvest[1] | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Species | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
| Wheat straw | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Corn stover | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 1.00 | 0.00 | 0.00 |
| Old world bluestem | 0.80 | 0.75 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 1.00 | 1.00 | 0.95 | 0.90 | 0.85 |
| Native tall prairies | 0.80 | 0.75 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 1.00 | 1.00 | 0.95 | 0.90 | 0.85 |
| Native mixed prairies | 0.80 | 0.75 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 1.00 | 1.00 | 0.95 | 0.90 | 0.85 |
| Native short prairies | 0.80 | 0.75 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 1.00 | 1.00 | 0.95 | 0.90 | 0.85 |
| Bermudagrass | 0.80 | 0.75 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 1.00 | 1.00 | 0.95 | 0.90 | 0.85 |
| Tall fescue | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 0.90 | 0.80 | 0.75 | 0.00 | 0.00 | 0.00 |
| Switchgrass | 0.80 | 0.75 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 1.00 | 1.00 | 0.95 | 0.90 | 0.85 |

Source: Taliaferro (2004)

[1] The contents of this Table are referred to as *YAD* in equations 4.7 and 4.8.

months of the year. The contents of Table 8 were obtained through consultations with expert opinion (Taliaferro, 2004). The contents of Table 8 are referred to as Yield Adjustment Factor (*YAD*) in equations 4.7 and 4.8.

Thorsell, in cooperation with an agricultural engineer, designed a harvest unit consisting of a coordinated set of machines 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. The cost of a harvest unit includes labor cost of $250,000 per 9 months for a harvest crew of 10 workers. Crop residues can only be harvested in four months. Consequently, the labor cost in the crop residue models was reduced to account for the four-month harvest period. For the crop residue model the labor cost was determined as $250,000 ÷ 9 = $27,777.78, then labor cost for four months is given as $27,777.78 per month× 4 months = $111,111.11. Therefore the cost of a harvest unit was given as $580,000 - $250,000 + $111,111.11 = $441,111. Similar calculations were done to get the cost of a harvest unit to be used in the CRP model. The cost of a harvest unit in the restricted model of the CRP model is $413,333.

A single harvest unit provides a capacity of 340.67 tons per day. Based upon Table 7 in Thorsell's thesis the estimated tons per hour per baler is 15.5 tons/hour for yields of 5 ton/acre, 15.1 tons/hour for yields of 3 tons/acre and 13.6 tons/hour for yield of 1 ton/acre.  A single harvest unit that harvests 341 tons/day includes three balers used 8 hours per day.  This translates to 14.2 tons/hour /baler, which is within the estimates by Thorsell.  Her estimate reflects substantial economies of size.  In the present study the harvest unit with throughput capacity as designed by Thorsell is incorporated into the 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.  Monthly capacity depends upon the number of harvest days per month and the number of endogenously determined harvest units.  An estimate of the expected number of harvest days per month based upon historical weather is incorporated.

Reinschmiedt determined, from a producer survey, the amounts of field time lost as a result of alternative amounts of rainfall for given soil type and soil moisture conditions prior to the rain.  Kletke and Sestak used Reinschmiedt's findings to determine the days available for fieldwork for regions of Oklahoma, by month and soil type, for three timeliness confidence levels (i.e. 95%, 85%, and 70%).  For example, in the Panhandle, for the month of June, they reported that at least 17.50 days will be available for field work in 95% of the years (i.e. 19 out of 20 years).  They reported 22.25 days available in 85% of the years (i.e. 17 out of 20 years) and that there will be 25.00 days available 70% of the years (14 out of 20 years).  In this study the conservative 95%-of-the-years confidence level was chosen.  For Oklahoma regions where fieldwork days were differentiated by two different types of soils, the number of fieldwork days for that region and in that month was determined by taking the average of the two reported numbers of days.  Kletke and Sestak defined Oklahoma regions as Panhandle, Southwest, Central and East.  But this did not concur with the definitions of Oklahoma regions in this study (refer to Table 4). Consequently an Oklahoma map from the Oklahoma Agricultural Statistics Services was used to synchronize the two definitions. By corresponding the county names from the map obtained from the Oklahoma Agricultural Statistics Services with the county names in this study the fieldwork days were then allocated to each county by month.

Table 9 gives the days available for fieldwork for each month and for the regions of Oklahoma as defined by Kletke and Sestak. Figure 11 is the map of Oklahoma showing the agricultural statistics regions. The two Panhandle counties of Harper and Ellis together with counties in West Central and Southwest (refer to map) were all considered as the Southwest region (Table 9). Counties in North Central, Central and South Central (Figure 11) were all considered as Central (Table 9). Finally, counties in Northeast, East Central and Southeast (Figure 11) were all considered East (Table 9). These assumptions were done to harmonize with the data from Reinschmiedt, and Kletke and Sestak (Table 9) and counties in this study.

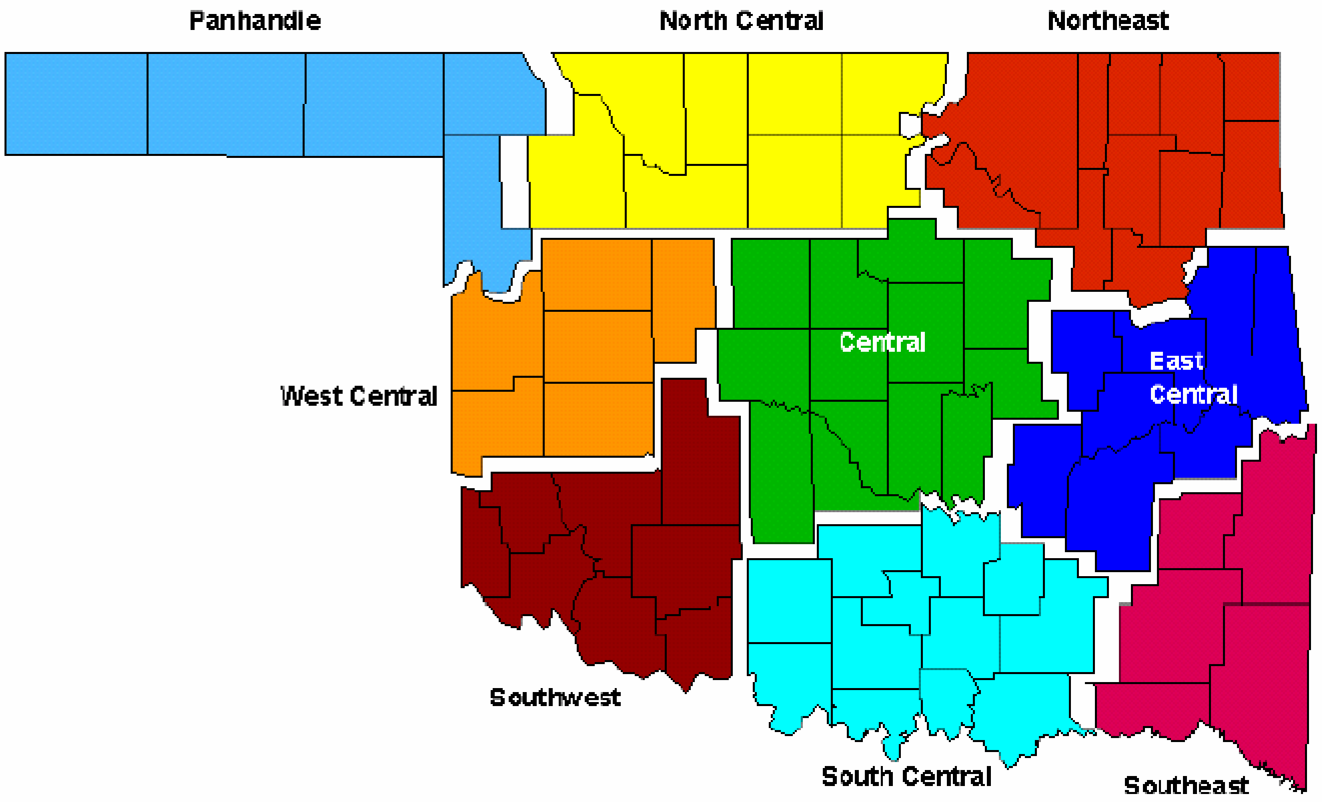
At the biomass supply point, storage is the only post-harvest activity considered in the model. Various feedstock types deteriorate at different rates. However, because of lack of data, this model uses a single deterioration rate for all biomass types. Specifically, it is assumed that a 0.5 percent loss in quantity will be incurred every month the biomass stays in storage (Huhnke, 2004). LCB stored in-field is assumed to be stacked and covered with a plastic tarp. It is assumed that the cost of storing biomass in field would be \$2.00 per ton (Huhnke, 2004), regardless of how long the biomass material stays in the storage. Biomass storage and processing activities at the plant are discussed in the next section. The model breaks the year into 12 discrete periods

**Table 9. Days Available for Field Work for Various Regions of Oklahoma**

| Month | Panhandle | Southwest | Central | East |
|---|---|---|---|---|
| January | 28.25 | 21.50 | 18.88 | 16.75 |
| February | 24.50 | 18.13 | 18.75 | 13.00 |
| March | 21.25 | 19.75 | 19.00 | 14.25 |
| April | 21.50 | 15.88 | 13.25 | 11.00 |
| May | 18.00 | 10.75 | 9.25 | 10.25 |
| June | 17.50 | 15.00 | 12.50 | 11.25 |
| July | 17.00 | 19.13 | 16.00 | 18.75 |
| August | 18.50 | 18.50 | 19.25 | 18.00 |
| September | 19.00 | 14.38 | 16.13 | 13.75 |
| October | 22.75 | 14.50 | 15.75 | 14.50 |
| November | 24.00 | 19.38 | 17.88 | 15.00 |
| December | 26.50 | 21.88 | 18.75 | 14.25 |

Source: Reinschmiedt (1973)

Kletke and Sestak (1991)



Source: Oklahoma Agricultural Statistics Service

Figure 11. Map of Oklahoma showing the agricultural statistics regions

(months) enabling a flow of feedstock to a biorefinery throughout the year. All decisions about production, harvesting, storage, shipment and processing of biomass can be done in any of the 12 discrete periods (i.e. months).

## Facility-Related Estimates

The objective function of the model in this study maximizes the net present worth of a biomass biorefinery plant over a 15-year period of stream of annual revenue less annual operating cost and the initial investment cost. This study assumes a market discount rate of 15 percent (Kaylen et al.). Annual revenue accrues from the sales of the pseudo-product. The eleven (11) prospective plant locations were selected on the basis of biomass relative density, proximity to the biomass producing counties, and availability of road infrastructure. All the eleven prospective plant locations (counties) were identified in Oklahoma. These counties include Canadian, Comanche, Custer, Garfield, Jackson, Okmulgee, Payne, Texas, Pontotoc, Washington, and Woodward. Each of these locations, if in the basis, will involve construction and installation of a processing facility and a biomass storage facility. The costs associated with these facilities will vary by plant size. In this study, a processing plant with capacity to process 2,000 tons of biomass per day is assumed to be medium in size. If we assume that three weeks storage capacity is enough as contingency for most biomass supply disruptions, a plant of this capacity will need to be equipped with 42,000 tons of biomass storage facility. With this processing and storage capacity of the plant, the study assumes the construction and installation costs for the 2,000 tons per day plant will be $100 million (Johannes, 2004) and $1,884,000 (Huhnke, 2004) for the processing and storage facilities, respectively (Table 10).

A factor of 0.5 was used to scale the facilities up or down to get a large plant or a small plant, respectively. For the processing facilities, with an annual processing capacity of 2,000 tons of biomass a day regarded as “medium”, 2,000 x 0.5 = 1,000 tons a day and 2,000 ÷ 0.5 = 4,000 tons a day would be regarded as “small” and “large” processing facilities, respectively. Similarly, storage capacities of 42,000 tons, 42,000 x 0.5 = 21,000 tons, and 42,000 ÷ 0.5 = 84,000 tons correspond to “medium”, “small” and “large” storage facilities, respectively. For all the facilities a fifteen-year useful life and zero salvage value were assumed. At the plant, in-storage minimum biomass inventory and storage losses are assumed to be equal to zero and 0.1 percent, respectively.

For both processing and storage facilities it was assumed that doubling capacity increases construction costs by 70 percent (Johannes, 2004). Hence 70 percent was used to adjust the medium plant costs to large and small plants. Table 11 gives the facility capacity and cost data. Annual operating and maintenance costs are computed as fixed proportion of total investment. In this study, these proportions are assumed to be 2% (Huhnke, 2004) for storage and 5% (Johannes, 2004) for processing facilities.

**Table 10. Construction and Equipment Cost for an On-Site Biomass Storage Facility for a 2,000-Ton LCB per Day Plant**

| Item Description | Unit | Quantity |
|---|---|---|
| Storage Facility | $ft^2$/ton | 9 |
| Storage period | week | 3 |
| Construction costs | | |
| Facility cost | \$/$ft^2$ | 3 |
| Facility cost | \$/ton | 27 |
| Processing facility capacity | | |
| Biomass | ton | 700,000 |
| Biomass storage capacity | ton | 42,000 |
| Subtotal construction costs | dollar | 1,134,000 |
| Equipment | | |
| Payloaders (2 x \$250,000) | dollar | 500,000 |
| Grinding equipment | dollar | 250,000 |
| Subtotal equipment costs | dollar | 750,000 |
| Total fixed costs for biomass storage facility | dollar | 1,884,000 |
| Annual operating and maintenance cost (2% of total fixed costs) | dollar | 37,680 |

Source: Personal Communication with Huhnke (2004) and Epplin (2004).

**Table 11. Facility Capacities and Construction and Installation Costs by Plant Size**

| | Facility Monthly Capacity | | Facility Fixed Costs ('000$) | | Total Plant |
|---|---|---|---|---|---|
| Plant Size | LCB Processing (tons /day) | Biomass Storage (tons) | Processing | Storage | Costs ('000$) |
| Small | 1,000 | 21,000 | 58,824 | 1,108 | 59,932 |
| Medium | 2,000 | 42,000 | 100,000 | 1,884 | 101,884 |
| Large | 4,000 | 84,000 | 170,000 | 3,203 | 173,203 |

# CHAPTER V

# RESULTS

## Comparisons between the Endogenous and Exogenous Harvest Cost Models

The first objective was to determine how the method of modeling harvest and procurement cost changes the cost to deliver a ton of LCB (from crop residue, indigenous native prairies, improved pastures, Conservation Reserve Program (CRP) land, dedicated switchgrass) to a biorefinery that has the capacity to process 1,000, 2,000, or 4,000 dry tons per day. To achieve this objective, two models were formulated and solved. These models are labeled in Table 12 as (i) endogenous harvest cost model and (ii) exogenous harvest cost model due to the differences in assumptions. The endogenous harvest cost model endogenously determines the optimal number of harvest machines required and the harvest cost. The exogenous harvest cost model has a predetermined harvest cost per ton. The GAMS code for the base model is presented in Appendix B. Sensitivity analyses were done for the endogenous harvest cost model (which is referred to as the base model) and the results are presented in this section.

Table 12 presents the comparisons of results for the endogenous and exogenous harvest cost models for a large biorefinery plant (i.e. with capacity to process 4,000 dry tons of biomass per day). For the exogenous harvest cost model, a harvest charge of

## Table 12. Results of Models Solved to Determine How the Method of Modeling Harvest and Procurement Cost Changes the Cost to Deliver a Ton of LCB to a Biorefinery That Can Process 4,000 Dry Tons Per Day

| | Model Comparisons | |
|---|---|---|
| Item | Endogenous Harvest Cost | Exogenous Harvest Cost |
| Biomass Acquisition Cost ($/ton) | 9.46 | 9.31 |
| Harvest Cost ($/ton) | 10.72 | 10.58 |
| Field Storage Cost ($/ton) | 0.39 | 0.39 |
| Transportation Cost ($/ton) | 14.51 | 14.41 |
| Total Cost of Delivered Feedstock ($/ton) | 35.37 | 34.91 |
| Harvest Units (Number)[a] | 26 | Not Applicable |
| Average Investment in Harvest Machines ($,000)[b] | 15,340 | Not Applicable |
| Harvested Acres | 945,760 | 1,009,219 |
| Total Biomass Harvested (tons) | 1,406,245 | 1,411,498 |
| Biomass Processed (tons) | 1,400,000 | 1,400,000 |
| Number of Biomass Feedstock Harvested | 7 | 7 |
| Average Distance Hauled (miles) | 106 | 105 |
| Plant Location | Canadian | Custer |
| Size of Plant | Large | Large |
| Capacity Usage (%)[c] | 100% | 100% |

[a] A harvest unit includes ten laborers, three mowers, three rakes, three balers, nine tractors, and one transport stacker.

[b] The average investment in harvest machines is calculated as half the price of the machine plus the salvage value summed across all machines.

[c] The biorefinery is expected to operate 350 days per year. The model was restricted to choose only one plant location and size.

$10.58 per ton was assessed for all tons harvested. For the endogenous harvest cost 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.

With the exception of an equal charge for in-field storage cost, all other per ton costs are slightly lower for the exogenous harvest cost model than for the endogenous harvest cost model. For the endogenous harvest cost model the harvest cost per ton is $10.72 compared to $10.58 for the exogenous harvest cost model. Similar harvest cost results were reported by Cundiff, Cundiff and Marsh, Epplin (1996), Sokhansanj and Turhollow, Ho (1985b) and English et al. Restrictions in the endogenous harvest cost model regarding harvest capacity of machinery and available harvest days result in higher harvest cost than the exogenous harvest cost model. Therefore, by not accounting for harvest capacity constraints that are determined by available harvest days and optimal number of harvest machines the exogenous harvest cost model underestimates the harvest cost. Table 12 shows that the total cost to deliver a ton of biomass is $35.37 and $34.91 for the endogenous and exogenous harvest cost models, respectively. The exogenous harvest cost model has a lower total cost of delivered ton of biomass because it has lower harvest cost, biomass acquisition cost and transportation cost. The biomass acquisition cost is lower in the exogenous harvest cost model because it harvested more biomass from the CRP land than the endogenous harvest cost model. This resulted in a higher land rent cost per ton in the exogenous harvest cost model than the alternative model. Transportation cost per ton is lower in the exogenous harvest cost model because biomass is hauled from a shorter distance than the alternative model (Table 12). Therefore, by modeling harvest cost endogenously may underestimate the total cost to deliver a ton of biomass to a biorefinery. Similar results were reported by Epplin (1996).

Table 12 shows that the optimal number of harvest units for the endogenous harvest cost model is 26, which will require an average investment of about $15.3 million. Since the exogenous model assumes exogenously determined harvest cost it does not endogenously determine the number of harvest units. In the case of the endogenous harvest cost model the large (4,000 dry tons of biomass per year) biorefinery would optimally process 1.4 million tons of LCB annually harvested from 945,760 acres of land. Due to in-storage losses more biomass must be harvested than is required to meet the capacity of the plant. The model finds it optimal to harvest 1,406,245 dry tons biomass feedstock to suffice the requirements of the large biorefinery. LCB is harvested from seven of nine potential biomass feedstock. The nine potential biomass feedstock are wheat straw, corn stover, old world bluestem, bermuda grass, tall fescue, native tall grass, native short grass, mixed native grass and switchgrass. Biomass feedstock not harvested include tall fescue and switchgrass. The biomass feedstock is hauled to a large biorefinery optimally located in Canadian county from an average distance of 106 miles. The plant usage is at 100% throughout its lifespan.

On the other hand, Table 12 shows that the large (4,000 dry tons of biomass per day) biorefinery optimally selected by the exogenous harvest cost model would also optimally process 1.4 million tons of LCB annually harvested from 1,009,219 acres of land. The exogenous harvest cost model finds it optimal to harvest 1,411,498 dry tons biomass feedstock to suffice the requirements of the large biorefinery. Since the exogenous harvest cost model does not endogenously determine the number of harvest machines to be used therefore it has no restrictions in terms of harvest capacity of machines. Consequently, it harvests more acres and tons of biomass than the alternative model. This leads to a higher land rent per ton incurred than the alternative model (Table15). Similarly LCB is harvested from seven of the nine potential biomass feedstock. The biomass feedstock is hauled to a large biorefinery optimally located in Custer county from an average distance of 105 miles. As in the endogenous harvest cost model the plant usage is at 100%. Notice that by modeling harvest costs as exogenous the optimal plant location changes from Canadian county to Custer county. This way of modeling also affects the allocation of acres and tons harvested across the harvest periods (months).

Figure 12 shows the graph of harvested land by month. Notice that the exogenous harvest cost model optimally harvests more acres in the months of July, August and September with a high peak in the month of July. On the contrary, the endogenous harvest cost model has more or less a steady amount of harvest acres. The endogenous harvest cost model has monthly harvest capacity constraints hence can only harvest a given quantity of land in each month. The daily throughput capacity for the endogenous harvest cost model is based upon tons harvested not acres of land. The endogenous harvest cost model also has restricted number of harvest days in each month due to weather changes hence the tons and acres of biomass harvested not only depend on the capacity of the harvest unit but also on the available field days in that particular month.

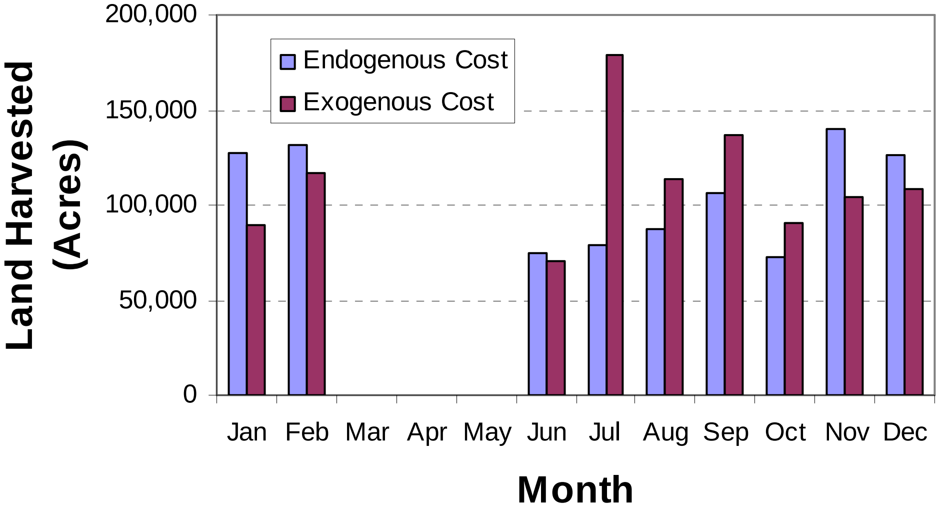


**Figure 12. Total number of acres harvested from all supplying counties in each month for the endogenous and exogenous harvest cost models**

Figure 13 gives the distribution of acres of biomass feedstock harvested in four of the five regions of Oklahoma. In both the endogenous and exogenous harvest cost models most of the harvesting is done in the Northwest (NWEST) and Southwest (SWEST) regions with the exogenous harvest cost model harvesting more acres in both cases than the endogenous harvest cost model. In the Northeast (NEAST) and Southeast (SEAST) regions the exogenous harvest cost model harvests less quantities of land than the endogenous harvest cost model. This is why the exogenous harvest cost model has less hauling distance than the endogenous harvest cost model. The acres harvested are restricted to 10% of total acres. In the endogenous harvest cost model the harvest units are restricted by monthly harvest capacity and biomass in the field incur field losses. Therefore, to acquire the required quantity of biomass the endogenous harvest cost model hauls extra biomass feedstock from longer distances (i.e. eastern Oklahoma region) than the exogenous model.

Harvesting of biomass is more concentrated in the Western regions because in both modeling methods the plant locations are in the Northwest part of the state (i.e. Custer and Canadian). The Northwest region has the largest number of acres harvested of all the regions, with the endogenous harvest cost model harvesting almost half the total harvested land (45 percent) and the exogenous harvest model harvesting over half of total harvested land (54 percent). For the endogenous harvest cost model, about 46 percent of the acres harvested in the Northwest region are under mixed native prairie grasses followed by wheat straw (25 percent). The proportion of acres harvested under tall native prairies in the Northwest region is 7 percent. A similar trend of results was observed with the exogenous harvest cost model for the Northwest region. The trend is different in the Southwest region. For the endogenous harvest cost model, 37 percent of the total harvested acres in the region are under mixed native prairies followed by native tall

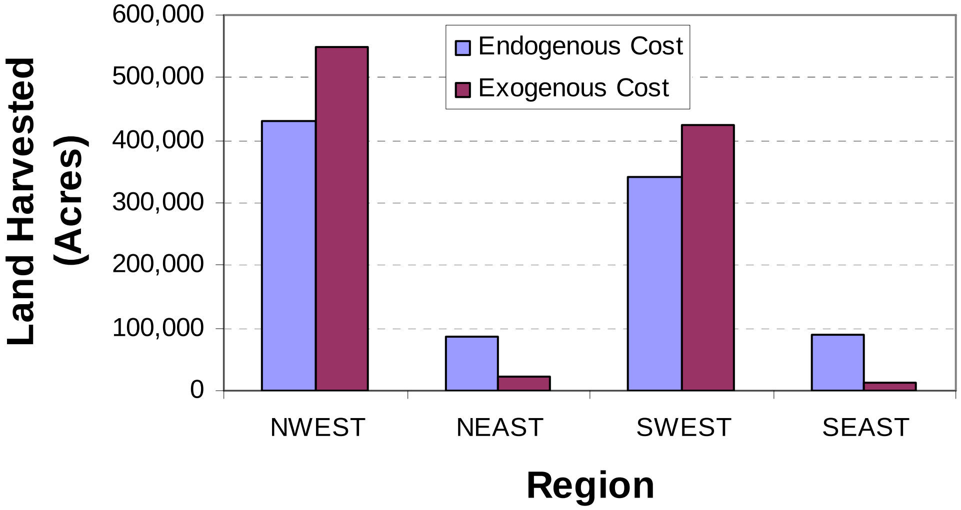


**Figure 13. Total number of acres harvested from all supplying counties in each region for the endogenous and exogenous harvest cost models**

grasses (30 percent). Only 13 percent of the total harvested acres are under wheat straw. For the exogenous harvest cost model, 31 percent of the total harvested acres in the region are under mixed native prairies followed by both native tall grasses and wheat straw (each at 25 percent of total harvested land). Counties in the Northeast and Southeast regions contribute less harvested acres than those in Northwest and Southwest regions. For the endogenous harvest cost model, the Northeast and Southeast regions each contributes 9 percent of the total harvested acres. For the exogenous harvest cost model, 2 percent and 1 percent of the total harvested acres are harvested from Northeast and Southeast regions, respectively. Unlike the Northwest and Southwest regions, the Northeast and Southeast regions supply a large proportion of one species of biomass feedstock i.e. more than 90 percent is land under native tall grass. This trend is the same for both the endogenous harvest cost model and the exogenous harvest cost model. No land is harvested in the Panhandle region of Oklahoma.

Figure 14 supports the above presented discussion. It presents a chart of the number of acres of land harvested for each optimally selected feedstock type. The abbreviations on the x-axis are defined as: WHS = wheat straw, CNM = mixed native grass grown on CRP land, NAS = short native grass, CST = corn stover, NAT = tall native grass, IBE = bermuda grass, COW = old world bluestem grown on CRP land, NAM = mixed native grass grown on grassland, and IOW = old world bluestem grown on pastureland.

Native tall and native mixed prairie grasses dominate in acres harvested followed by wheat straw for both the endogenous and exogenous harvest cost models. Native prairie grasses are preferred because unlike other biomass species they do not require

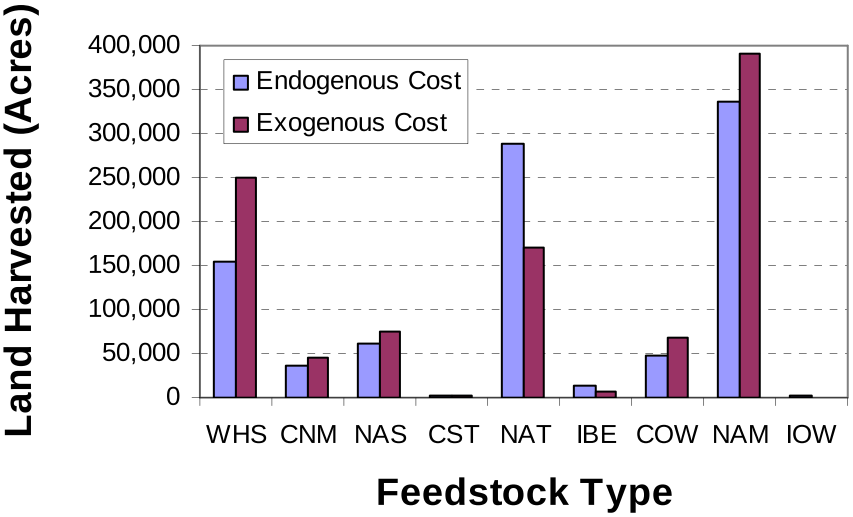


**Figure 14. Total number of acres harvested from all supplying counties by biomass feedstock type for the endogenous and exogenous harvest cost models**

nitrogen fertilizer and hence have no maintenance costs. Crop residues are also another group of biomass feedstock that do not require nitrogen fertilizer, however, due to its low occurrence in the state, especially in the Northwest and Southwest regions, less corn stover is harvested. Switchgrass may not be preferred to other biomass feedstock because besides maintenance costs it has establishment cost of $11.22 per acre. Switchgrass can only come into the solution if some of the cropland is allocated to its growth thereby incurring an establishment cost.

The exogenous harvest cost model harvests more acres of native mixed grasses and wheat straw than the endogenous harvest cost model, which harvests more acres of the native tall prairie grass. This is because the endogenous model harvests more acres of biomass in the eastern region, which has more than 90% of native tall grass, than the exogenous harvest cost model. The acres and type of grass harvested depend on the predominant grass species in the county where the plant is located and other counties that are supplying biomass to the plant. Interchangeably, location of the plant depends on the availability of an economical and steady source of biomass feedstock.

Figure 15 presents tons of biomass harvested in each month for both the endogenous harvest cost model and the exogenous harvest cost model. Similar to the acres harvested, the exogenous harvest cost model optimally harvests most of the required tons of biomass (more than 50 percent) in the months of July, August and September with most of it (22 percent) harvested in the month of July. This is consistent with the highest level of the yield adjustment factor ( $YAD = 1.00$ ) for most of the feedstock, including tall native prairies (see Table 8). The *YAD* which is the proportion of potential yield by harvest month is equal to one for all feedstock in the months of July, August and September, except tall fescue grass. The value of *YAD* starts declining in the month of October and continues to reduce by 0.05 in each month until the month of February. For the month of March through May *YAD* is equal to zero meaning that no harvesting can be done, consequently, all the shipments to the biorefinery plant are drawn

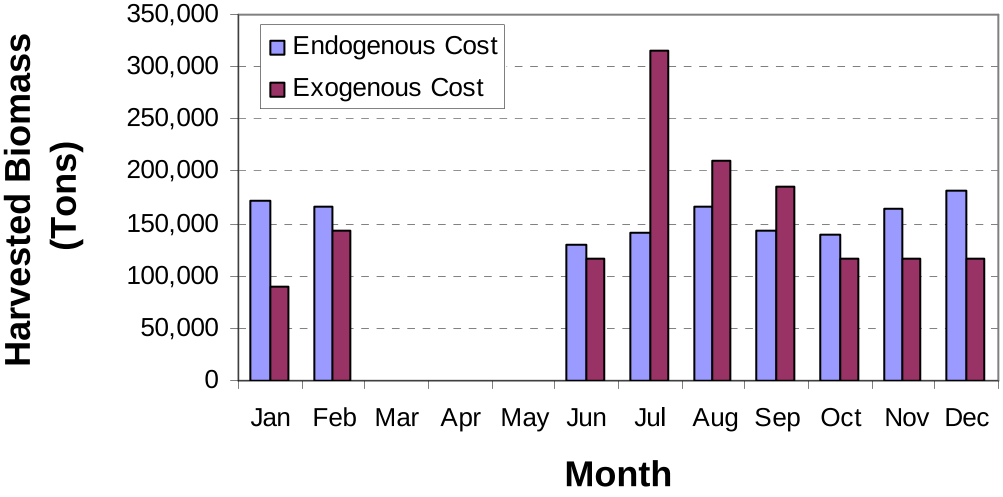


**Figure 15. Total dry tons of biomass harvested from all supplying counties in each month for the endogenous and exogenous harvest cost models**

from the in-field storage. Crop residues, however, can only be harvested during the months in which the main crop is being harvested. This is why wheat straw and corn stover have high yield adjustment factors (*YAD* = 1.00) only in periods June-July and September-October, respectively. For all other months, *YAD* = 0 for these crop residues.

On the contrary the endogenous harvest cost model has more or less a steady amount of harvested tons. The endogenous harvest cost model harvests lower amounts in the months of June, July, August and October. Unlike the exogenous harvest cost model, the endogenous harvest cost model has monthly capacity constraints on the quantity of biomass harvested by the machinery hence can only harvest a given quantity of biomass feedstock in each month. The endogenous harvest cost model also has restricted number of field workdays in each month in which harvesting could be done. This is so due to periodic weather changes hence the quantity of biomass that can be optimally harvested not only depends on the capacity of the harvest unit but also on the available field workdays in that particular month. Due to the restrictions the endogenous harvest cost model barely takes advantage of high levels of *YAD*.

By harvesting most of the required biomass in the first few months of the harvest season, the exogenous harvest cost model incurs more storage losses than the endogenous harvest cost model. Therefore, in total tons the exogenous harvest cost model harvests more than the endogenous harvest cost model to replace some of the lost biomass feedstock in storage.

Figure 15 indicates that when monthly harvest capacities are not imposed, harvest is concentrated in July, August and September. And, to harvest the estimated July LCB quantity a total of 53 harvest units would be required. Whereas, when monthly harvest capacities are imposed, the integer harvest unit model determines that it is optimal to only have 26 harvest units and to use them at capacity to harvest a variety of feedstock 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, 26 harvest units would require an average investment of $15.34 million. Whereas 53 harvest units would require an average investment of $31.27 million. Clearly, ignoring the influence of weather on the ability to harvest LCB feedstock can have substantial economic consequences.

Figure 16 presents the tons of biomass harvested by each biomass feedstock type. The abbreviated names of grasses on the x-axis are as defined earlier. As in the case of total acres harvested by biomass feedstock type (Figure 14), Figure 16 shows that a large quantity of the biomass feedstock shipments to the biorefinery would be native prairie grasses i.e. native tall and mixed native grasses. Wheat straw is the other biomass feedstock that is harvested in large quantities. While the exogenous harvest cost model harvests more tons of mixed native grasses and wheat straw than the endogenous harvest cost model, the latter harvests more tons of native tall grass than the exogenous harvest cost model. The reason for this difference is as stated above. Corn stover and old world bluestem are the least harvested biomass feedstock. Corn stover is harvested in low quantity because it exists in small quantities in the state and most corn is grown in the Panhandle region, which is not in the solution. Very little old world bluestem is harvested, in fact it is only the endogenous harvest cost model that selects this biomass

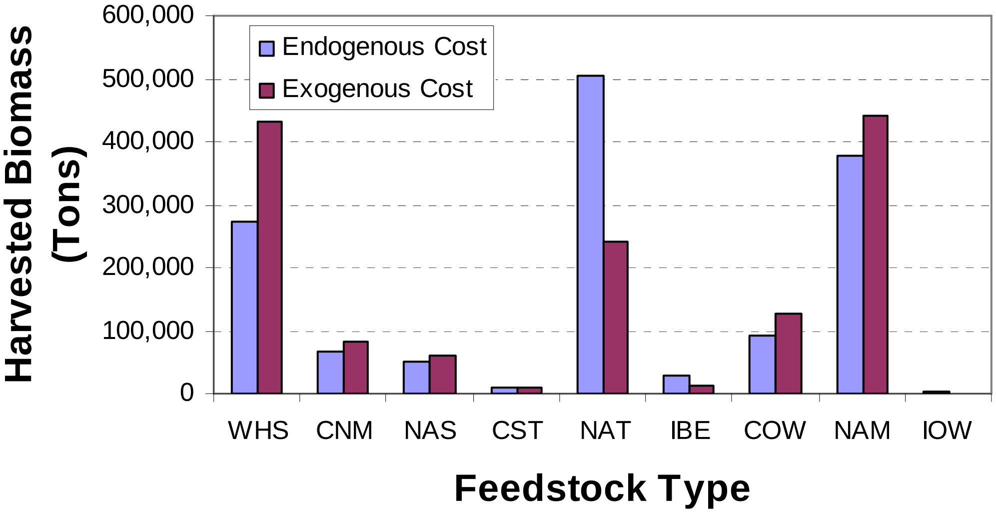


**Figure 16. Total dry tons of harvested biomass feedstock from all supplying counties by biomass feedstock type for both the endogenous and exogenous harvest cost models**

feedstock, because it requires maintenance cost and nitrogen fertilizer to produce and that, compared to bermuda grass (another improved pasture grass); it is grown on less acreage in the state as well as in the Northwest region where the plant would be located by both models.

In both the endogenous and the exogenous harvest cost models the optimally located biorefinery plant is used at full capacity. The biomass feedstock processed at the biorefinery can either be shipped directly from harvested biomass or from biomass kept in storage at the field. Biomass can also be shipped from the field to a storage facility at the biorefinery plant. Construction of each biorefinery plant comes along with construction of an on-site storage facility. Figure 17 includes a chart of the estimated quantity of feedstock stored per month at field sites for a 4,000-ton per day biorefinery from both the endogenous harvest cost and exogenous harvest cost models. In both models harvesting starts in the month of June. In the month of June and July the biomass feedstock harvested is wheat straw. For the exogenous harvest cost model, replenishment of storage reserves begins with the month of July. Increase in field storage inventory continues from July through the month of September. From the month of September field storage remains almost at the same high level up until the month of February when the harvesting is completed. At the end of the month of February the combined field and biorefinery storage inventory must be sufficient to provide feedstock until harvest may be resumed in the month of June. In-field storage reserves are drawn down until at the end of the month of May when inventory in field storage are reduced to zero.

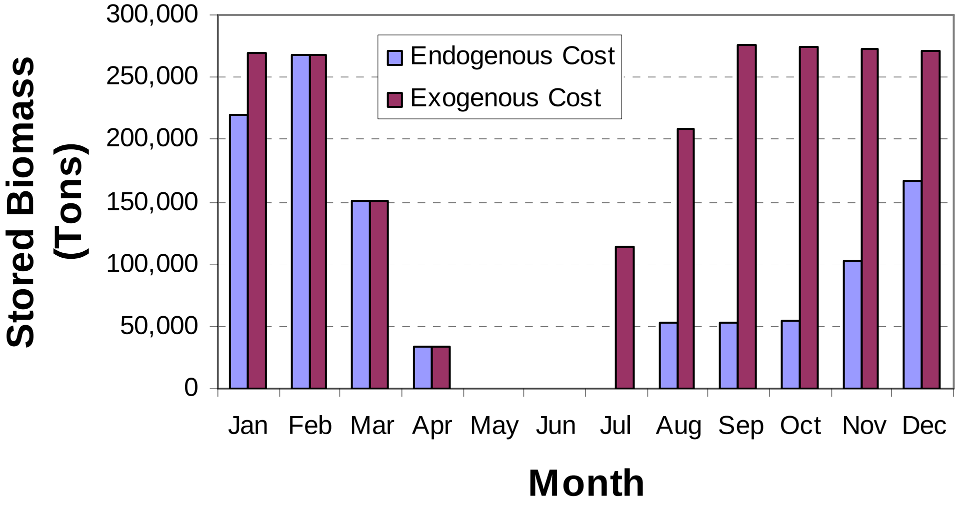


**Figure 17. Total dry tons of stored biomass feedstock from all in-field storage facilities in each month for both the endogenous and exogenous harvest cost models**

For the endogenous harvest cost model, field inventory storage increases gradually from August through February (Figure 17). The maximum quantity of required field storage for the endogenous harvest cost model is less than half of that required for the exogenous harvest cost model (at 1,100,939 tons for endogenous harvest cost model versus 2,136,938 tons for the exogenous harvest cost model). As is the case with the exogenous harvest cost model, at the end of the month of February the combined field and biorefinery storage inventory must be sufficient to provide feedstock until harvest may be resumed in the month of June. In-field storage reserves are drawn down until at the end of the month of May when inventory in field storage are reduced to zero. In both models all biomass feedstock harvested in the month of June is shipped straight to the biorefinery plant. Optimal harvest, storage and shipments pattern are determined based upon field losses and feedstock deterioration which was estimated to be 0.5 percent and 0.1 percent per month for in-field and on-site storage, respectively.

Minimum inventory constraints at the biorefinery were set to zero. Figure 18 includes a chart of the estimated quantity of feedstock stored per month at the biorefinery site for a large (4,000-ton per day) biorefinery for both the endogenous harvest cost model and the exogenous harvest cost model. As shown in Figure 18, inventory is

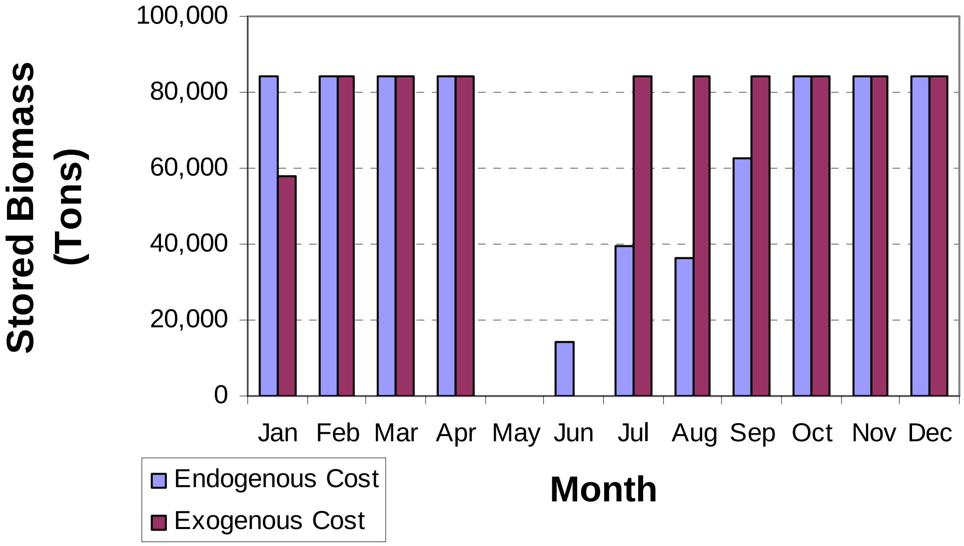


**Figure 18. Total dry tons of stored biomass feedstock at on-site storage facilities in each month for both the endogenous and exogenous harvest cost models**

reduced to zero at the end of the months of May and June for the exogenous harvest cost model, and at the end of the month of May only for the endogenous harvest cost model. Harvesting of biomass resumes in the month of June.

A single large plant has the capacity to process 4,000 tons of biomass a day. In this study it is assumed that the plant would operate for 350 days a year, hence total biomass feedstock processed by one large plant per year would be 4,000 tons/day x 350 days = 1,400,000 tons of biomass. Therefore the number of tons of biomass processed at the biorefinery per month would be 1,400,000 tons/year ÷ 12 months/year = 116,667 tons per month. The endogenous harvest cost model harvests 130,844 tons of biomass feedstock in the month of June (Figure 15). All is shipped to the biorefinery (Figure 19); none is put in field storage (Figure 17). Out of this 116,667 tons are processed by the biorefinery leaving 130,844 – 116,667 = 14,178 tons in the on-site storage (Figure 18). Considering that 0.1% is lost in the on-site storage this leaves 14,178 tons x 0.999 = 14,163 tons at the end of the month of June. In the month of July, the endogenous harvest cost model harvests 141,856 tons of biomass (Figure 15) and ships all of it to the biorefinery (Figure 19). Adding the shipped biomass tons to 14,163 tons of biomass in on-site storage from the previous month we get 141,856 + 14,163 = 156,019 tons. Of this 116,667 tons were processed leaving 39,353 tons in the on-site storage in that month (Figure 18). Considering that 0.1% is lost in the on-site storage this leaves 39,353 tons x 0.999 = 39,313 tons at the end of the month of July.

In the month of August, the endogenous harvest cost model harvests 166,886 tons of biomass (Figure 15), stores 53,436 tons in in-field storage (Figure 17) and ships

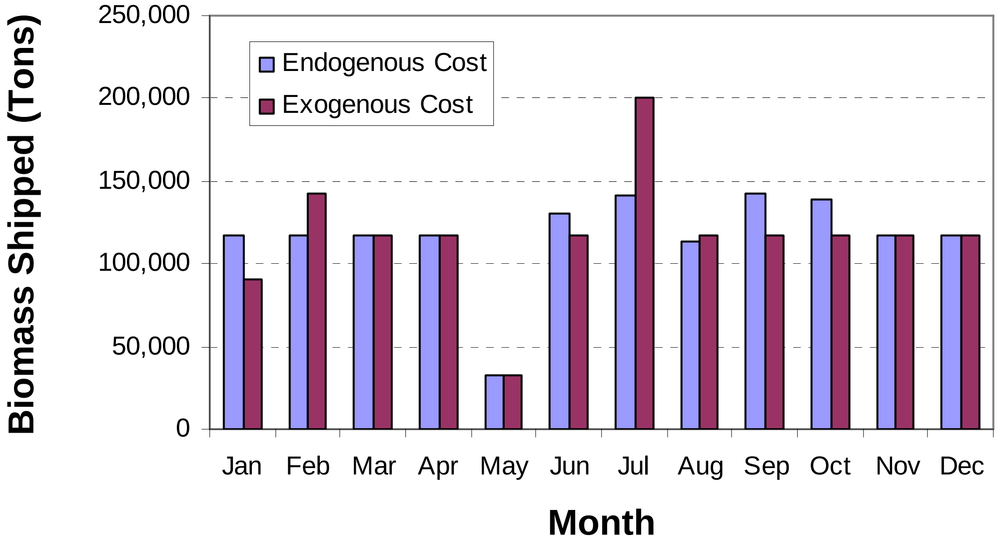


**Figure 19. Total dry tons of biomass feedstock shipments from the supplying counties to the biorefinery in each month for both the endogenous and exogenous harvest cost models**

113,449 tons to the biorefinery. Adding the August shipped tons of biomass to the 39,313 tons of biomass in on-site storage from the month of July we get 113,449 + 39,313 = 152,762 tons. Of this 116,667 tons were processed leaving 36,095 tons in the on-site storage at the end of the month of August (Figure 17). Biomass flow from harvest into in-field storage to shipments, on-site storage and processing continues for the rest of the other months until the end of harvesting season and harvesting resumes the following June.

A similar pattern of biomass shipment and storage is also observed with the exogenous harvest cost model. Nevertheless, differences in the optimal amounts of biomass selected in each period exist between these two models due to the underlining assumptions pertaining to the treatment of harvest cost in each model. For instance, in the month of June the exogenous harvest cost model harvest the exact quantity of biomass required for processing i.e. amount of biomass feedstock harvested, shipped and processed is equal. No biomass is stored either in in-field storage or at the on-site storage. From the month of July the exogenous harvest cost model harvests and ships adequate biomass quantities to feed the plant and put the remainder in on-site storage up to full capacity. The on-site storage is used to capacity by the exogenous harvest cost model in nine of the twelve months while for the endogenous harvest cost model the on-site storage is used to capacity in seven of the twelve months. In both cases the models account for storage losses in both in-field and on-site storage facilities in determining the quantity processed.

## Comparisons among Different Plant Sizes for the Base Model

In this study the exogenous harvest cost model is assumed to be the base model. Henceforth, the term base model will refer to the exogenous harvest cost model. Table 13 presents a comparison of results for the base model assuming a small, medium and large plant sizes (i.e. 1,000, 2,000, and 4,000 dry tons per day biorefinery). The table shows that, with the exception of the storage cost, all costs increase as the plant size increases. Hence the cost to deliver a ton of LCB feedstock to a biorefinery increase as the plant size increases. Increasing the plant size from 1,000 to 4,000 dry tons processed per day also increases the required harvest units, harvested acres, harvested biomass feedstock and the average distance from which biomass is hauled. When the model is restricted to a small and medium plant the plant location changes from Canadian county to Woodward county. Considering the large plant only (4,000 dry tons per day biorefinery), the model optimally selected 53 counties of 77 counties in Oklahoma as biomass supplying counties. In the model for the large plant the estimated expected cost

## Table 13. Comparison of Results for the Base Model from 1,000, 2,000 and 4,000 Dry Tons Per Day Plants

| | Biorefinery Size (tons/day) | | |
|---|---|---|---|
| Item | 1,000 | 2,000 | 4,000 |
| Biomass Acquisition Cost ($/ton) | 9.04 | 9.07 | 9.46 |
| Harvest Cost ($/ton) | 9.90 | 9.90 | 10.72 |
| Field Storage Cost ($/ton) | 0.39 | 0.39 | 0.39 |
| Transportation Cost ($/ton) | 10.49 | 12.89 | 14.51 |
| Total Cost of Delivered Feedstock ($/ton) | 30.05 | 32.51 | 35.37 |
| Net Present Worth ($,000) | 14,692 | 42,373 | 100,541 |
| Harvest Units (Number) | 6 | 12 | 26 |
| Average Investment in Harvest Machines ($,000) | 3,540 | 7,080 | 15,340 |
| Harvested Acres | 313,345 | 580,879 | 945,760 |
| Total Biomass Harvested (tons) | 351,557 | 703,096 | 1,406,245 |
| Biomass Processed (tons) | 350,000 | 700,000 | 1,400,000 |
| Number of Biomass Feedstock Harvested | 6 | 7 | 7 |
| Average Distance Hauled (miles) | 72 | 93 | 106 |
| Plant Location | Woodward | Woodward | Canadian |
| Capacity Usage (%) | 100% | 100% | 100% |

to deliver a ton of LCB feedstock is $35.37 which is substantially lower than the current delivery cost per ton of corn and hay. According to the USDA (USDA, 2005) the delivery cost for corn is $96.64 per dry ton and that of hay is $70.59 per dry ton. These delivery costs are higher by $61.27 per dry ton and $35.22 per dry ton for corn and hay, respectively, than the delivery cost of a dry ton of LCB feedstock.

Previous studies that have determined the cost of delivering a ton of biomass to a biorefinery have assumed that harvesting would be done by custom harvesters. Custom harvesting is more expensive than facility owned machinery due to added management costs and profit. This has resulted in these studies reporting higher costs to deliver a ton a feedstock than in this study. For instance studies by Cundiff and Harris, Worley and Cundiff, and Kaylen et al. reported a cost to deliver a ton of LCB feedstock of more than $50/dry ton. The delivery cost of a ton of LCB reported in this study is substantially lower than that which has been reported in previous studies. To minimize cost for the LCB biorefinery industry this study assumes a coordinated set of harvest machinery operated by specialized crew. This set of machinery and harvest crew known as harvest unit would develop in concert with the LCB biorefinery and would be owned by the processing facility. This would avoid high costs of custom harvesting and would provide more assurance of a steady flow of feedstock than using farmer-owned machinery. This study's finding of expected delivery cost of $35.37 per dry ton is similar to the finding by Epplin (1996) and Tembo, Epplin and Huhnke. Epplin reported a total delivery cost of $33.66/dry ton when he considered switch grass as the feedstock for biorefinery processing. Tembo, Epplin and Huhnke assumed a variety of biomass feedstock species and reported a delivery cost of LCB of $38.25 per ton.

## Sensitivity Analysis Results

A number of sensitivity analyses were done on a few parameters from the base model to determine how sensitive model results were to those particular parameters. What is considered the base model, in this case, is the model with endogenously determined harvest units and harvest cost (i.e. the endogenous harvest cost model). In most cases model parameters are not known with certainty, in other words, errors may be incurred in the estimation of such parameters or due to lack of adequate information certain parameter estimates may not be exact or close to the true parameter value. This section presents the results of a few model scenarios in which one parameter value was changed leaving all other parameters at their initial values as in the base model. The following are the scenarios chosen for sensitivity analyses: (i) in the first scenario the per ton acquisition cost of biomass (or the price of biomass per ton) was doubled (Doubled Price model); (ii) in the second scenario the number of days available in each month in which harvesting of biomass could be done were reduced by 50 percent (50% HD model); (iii) in the third the cost of a single harvest unit was increased by 50 percent (150% CHU model); (iv) in the fourth scenario the proportion of harvested acres was increased from 10% to 25% (25%Harv Acres); and (v) in the fifth and last scenario the proportion of harvested acres was increased to 35% (35%Harv Acres). Below is the discussion of the results for each scenario.

Table 14 gives a summary of some results associated with the base model in comparison to the sensitivity analyses. The first row shows that the biomass acquisition cost increased substantially in the first sensitivity analysis (when the biomass acquisition cost was doubled). As a result of doubling the cost of biomass feedstock the model purchased more biomass grown on CRP land than the base model to compensate for the increase in the biomass cost. Based on the assumptions used to determine the dollar amount per acre to be given to farmers who own CRP land, when the biomass purchase cost was increased the compensation on CRP land rent for harvesting the land was not doubled. Federal payments on CRP land vary depending on the soil characteristics of land, including land productivity. In scenarios four and five the biomass acquisition cost increased slightly. When the proportion of harvested acres was increased the biomass acquisition cost increased slightly higher than that of the base model because more land and, hence, more biomass could be harvested.

Table 14 also shows that harvest cost increased when the available harvest days in a month were reduced by 50% and when the cost of a harvest unit increased by 50%. But the increase in harvest cost is much more when the harvest days are reduced by 50%. When the numbers of days that are available for harvesting were reduced by half the cost of harvesting almost doubled. This is because more harvest machines would be required to do the same job when there are fewer days to harvest biomass than in the base model. In the case of increasing the cost of a harvest unit, harvest cost increased due to the increased cost of a harvest unit even though the number of harvest units in that scenario is less by one harvest unit than the base model. On the other hand increasing the proportion of acres harvested decreased the per ton harvest cost because less number of harvest units were required (Table 14).

Table 14 shows that all scenarios increased the total cost to deliver a continuous flow of biomass to a biorefinery except for scenarios four and five in which the proportion of harvested acres were increased. The increase is much more when the

**Table 14. Comparison of Results of the Base Model for Endogenous Harvest Cost with the Sensitivity Analyses for a Biorefinery That Can Process 4,000 Dry Tons Per Day (Large Plant)**

| | Comparisons of Base Model and Sensitivity Analyses | | | | | |
|---|---|---|---|---|---|---|
| Item | Base Model | Doubled Price | 50% HD | 150% CHU | 25%Harv Acres | 35%Harv Acres |
| Biomass Acquisition Cost ($/ton) | 9.45 | 17.43 | 9.36 | 9.36 | 9.47 | 9.59 |
| Harvest Cost ($/ton) | 10.72 | 10.31 | 20.63 | 15.47 | 10.31 | 9.90 |
| Field Storage Cost ($/ton) | 0.39 | 0.39 | 0.39 | 0.39 | 0.39 | 0.39 |
| Transportation Cost ($/ton) | 14.51 | 15.16 | 14.82 | 14.82 | 12.00 | 11.21 |
| Total Cost of Delivered Feedstock ($/ton) | 35.37 | 43.72 | 45.70 | 40.54 | 32.37 | 31.28 |
| Net Present Worth ($,000) | 100,541 | 31,890 | 15,680 | 58,074 | 125,291 | 134,158 |
| Harvest Units (Number) | 26 | 25 | 50 | 25 | 25 | 24 |
| Average Investment in Harvest Machines ($,000) | 15,340 | 14,750 | 29,500 | 14,750 | 14,750 | 14,160 |
| Harvested Acres | 945,760 | 1,022,834 | 1,023,450 | 1,024,467 | 1,169,894 | 1,268,909 |
| Total Biomass Harvested (tons) | 1,406,245 | 1,406,095 | 1,406,016 | 1,406,016 | 1,405,925 | 1,406,270 |
| Biomass Processed (tons) | 1,400,000 | 1,400,000 | 1,400,000 | 1,400,000 | 1,400,000 | 1,400,000 |
| Number of Biomass Feedstock Harvested | 7 | 7 | 7 | 7 | 6 | 7 |
| Average Distance Hauled (miles) | 106 | 112 | 109 | 109 | 85 | 78 |
| Plant Location | Canadian | Custer | Custer | Custer | Woodward | Woodward |
| Capacity Usage (%) | 100% | 100% | 100% | 100% | 100% | 100% |

number of harvest days are reduced by 50% followed by the double price model. This shows that the base model is very sensitive to the number of days available for field harvesting. Reducing the number of harvest days by half also adversely affects the net present worth and increases the average investment in harvest machines by almost double. Cundiff found that an increase in harvest days reduced per ton harvest costs by 10%. Feedstock acquisition cost is another important parameter for the economics of the biomass biorefinery. The increase in the feedstock acquisition cost adversely affects cost to deliver a ton of biomass to a biorefinery. Furthermore, proportion of harvested acres is an important parameter in the base model. If the proportion of harvested acres can increase substantially then the cost to deliver a ton of biomass would also decrease substantially.

Notice that all scenarios harvested more land than the base model. With the exception of scenarios four (25%Harv Acres) and scenario five (35%Harv Acres), all scenarios hauled biomass feedstock from longer distance than the base model with the first scenario hauling biomass the longest distance (Table 14).

## Sensitivity Analysis 1: Double Biomass Acquisition Cost

Figure 20 shows the graph of harvested land by month. Except for the months of October, December and January in which the double price model harvested more acres of biomass than the base model, the harvested land in all the other months does not significantly differ from the base model results. Overall, when the per ton cost of acquiring biomass feedstock is doubled the model harvests more land than in the base model and most of this land is harvested in the later months of the harvest season.

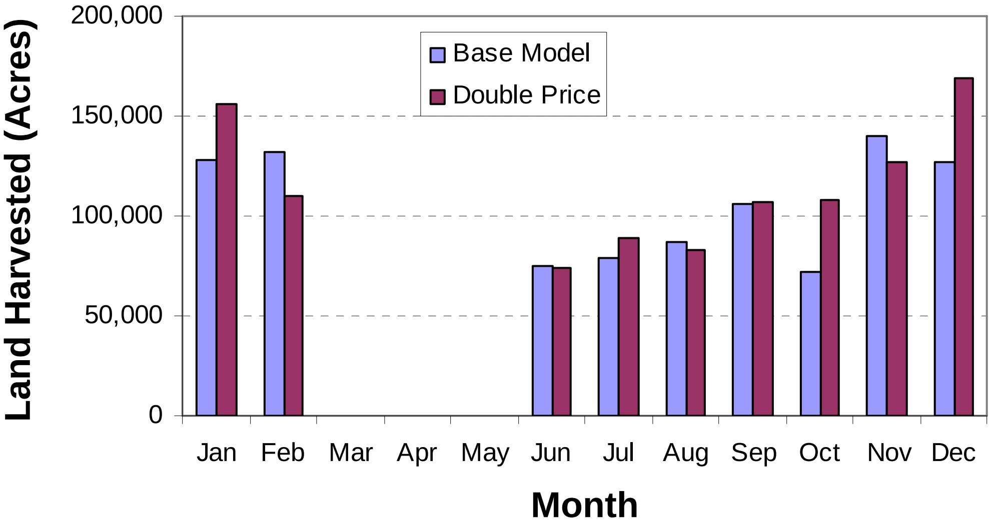


**Figure 20. Total number of acres harvested from all supplying counties in each month for the base model and double price model**

Figure 21 gives the distribution of acres of biomass feedstock harvested in four of the five regions of Oklahoma. Since in both models the selected plant locations are in Northwest region of Oklahoma, most of the harvesting is done in the western part of Oklahoma. Both the base model and the sensitivity analysis harvest more acres of biomass in Northwest and Southwest Oklahoma than in the Northeast and Southeast Oklahoma with the sensitivity analysis model harvesting more land as observed earlier. Figure 22 shows that native prairies dominate in acres harvested in both models. Figure 23 shows the tons of biomass harvested by month from both the base model and the double price model. No significant differences exist in the tons harvested in each month between the two models. Figure 24 shows that the base model harvests more quantity of native tall prairies and wheat straw than the double price model. On the other hand, the double price model harvests more biomass feedstock from the mixed native prairie grasses. No significant trends exist in the amount of biomass feedstock stored in the field (Figure 25). However, at the biorefinery the base model stores slight ly less biomass than double price model for the months of July through September (Figure 26). Overall, for on-site storage the base model stores less biomass feedstock than the double price model. The quantity of biomass shipments to the biorefinery plant (Figure 27) does not exhibit any significant changes due to doubling of biomass acquisition cost.

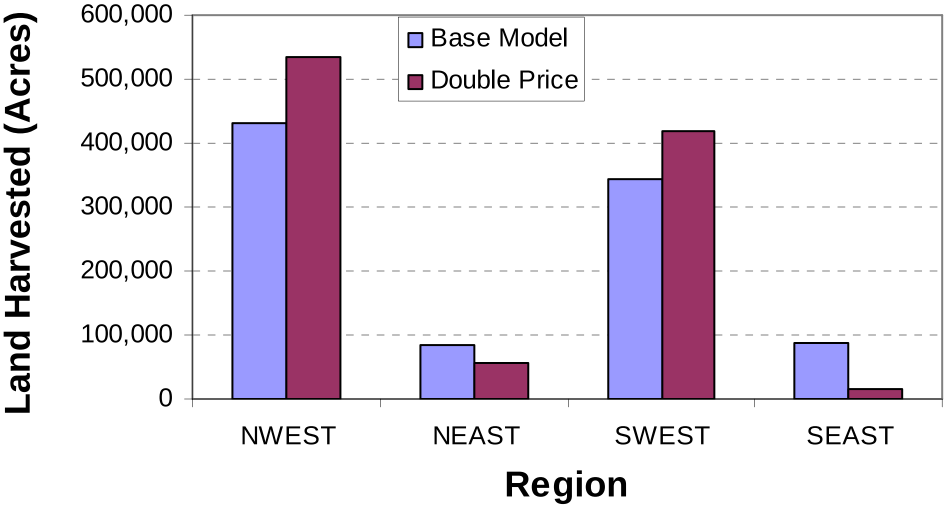


Figure 21. **Total number of acres harvested from all supplying counties in each region for the base model and double price model**

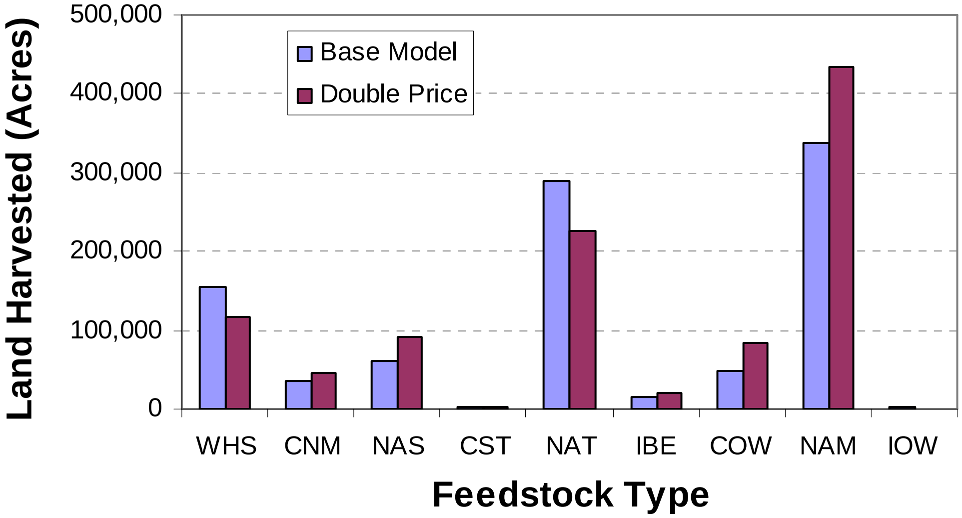


Figure 22. **Total number of acres harvested from all supplying counties by biomass feedstock type for the base model and double price model**

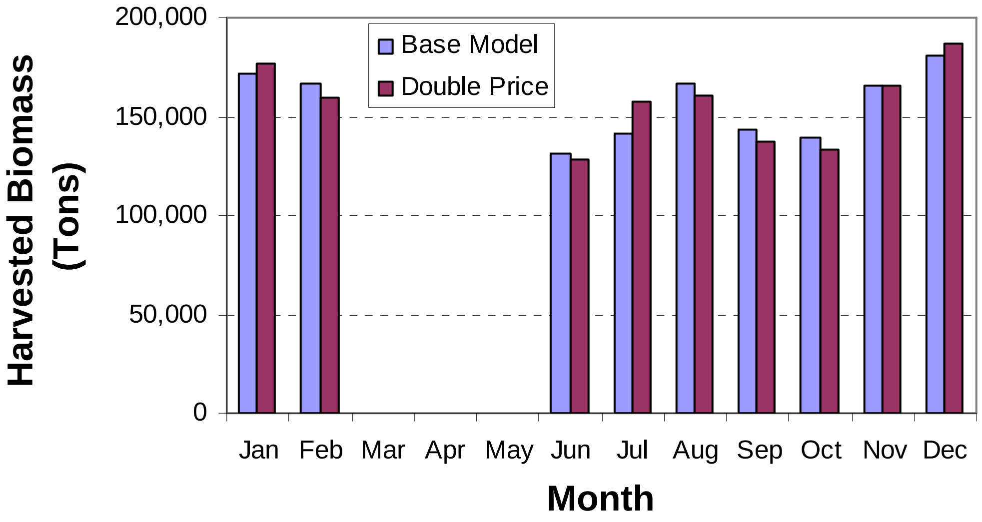


**Figure 23.** **Total dry tons of biomass harvested from all supplying counties in each month for the base model and double price model**

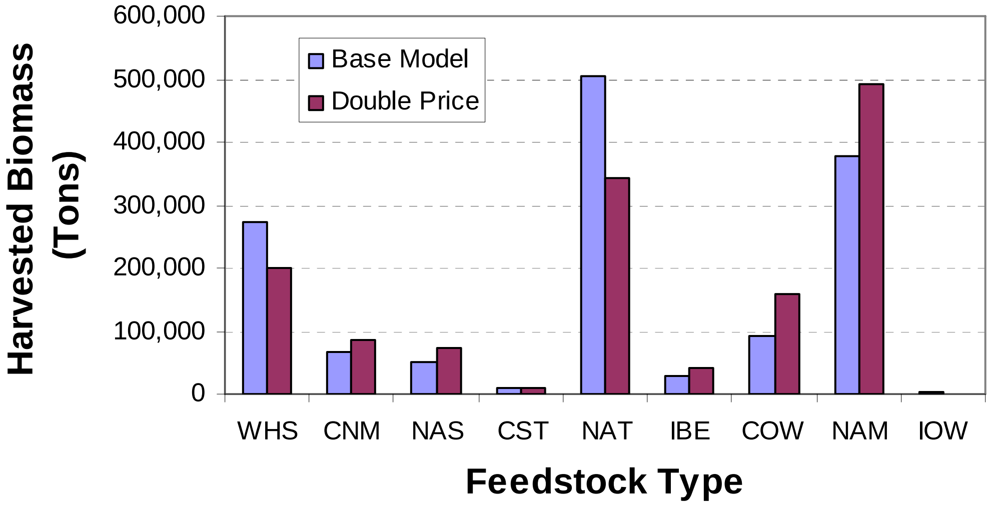


**Figure 24.** **Total dry tons of harvested biomass feedstock from all supplying counties by biomass feedstock type for both the base model and double price model**

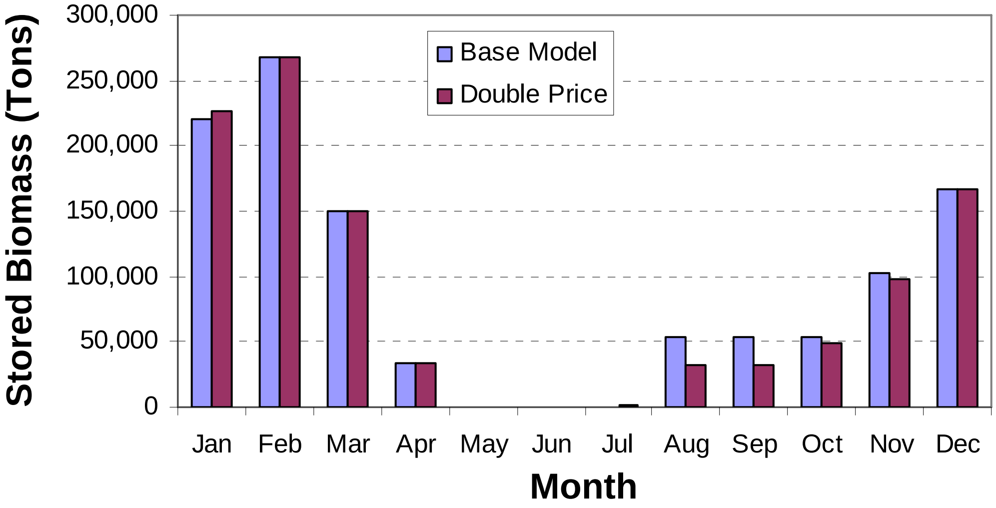


**Figure 25.** **Total dry tons of stored biomass feedstock from all in-field storage facilities in each month for both the base model and double price model**

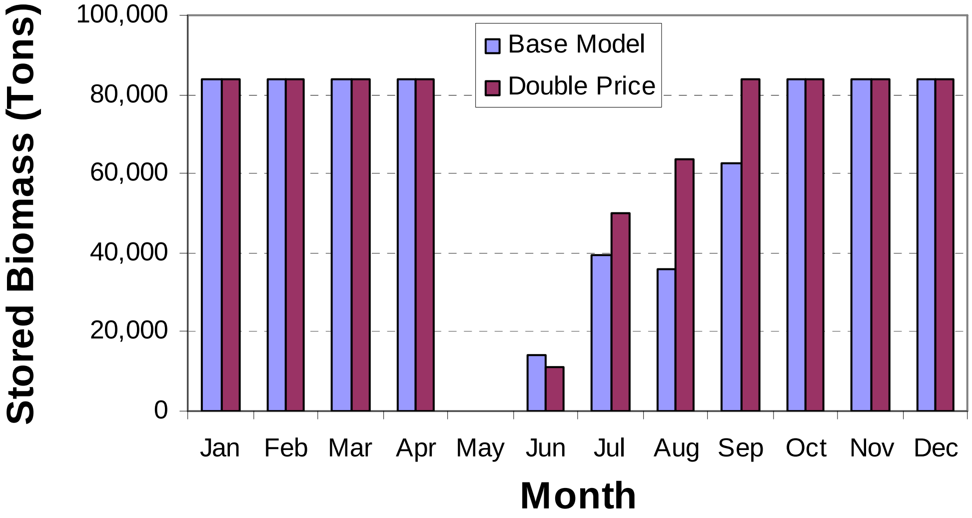


**Figure 26.** **Total dry tons of stored biomass feedstock at on-site storage facilities in each month for both the base model and double price model**

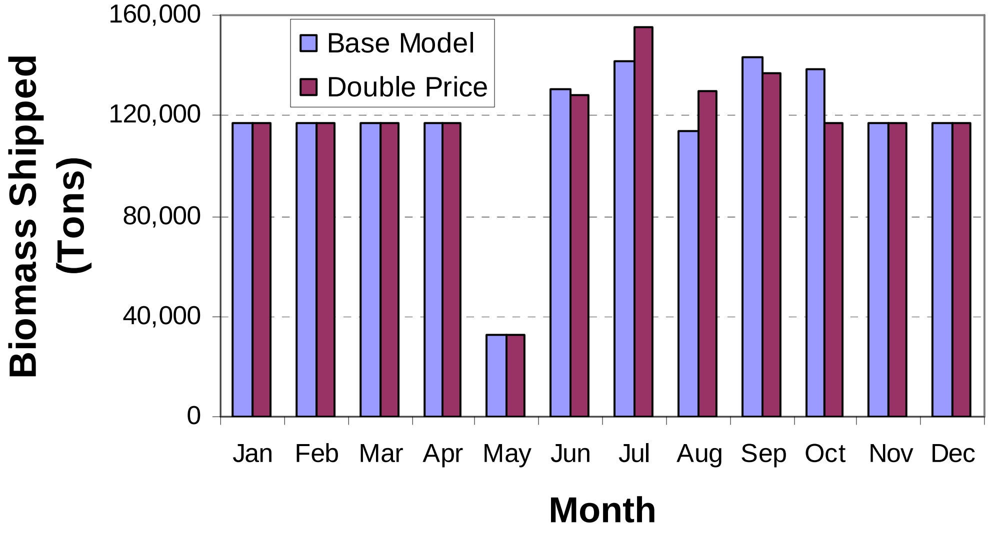


**Figure 27. Total dry tons of biomass feedstock shipments from the supplying counties to the biorefinery in each month for both the base model and double price model**

## <u>Sensitivity Analysis 2: Decreased Harvest Days by 50%</u>

Figures 28 through 35 give the detailed results of reduced harvest days model (50% HD model) versus the base model. Figure 28 show that most of the land would be harvested in the months between November and February with 50% HD model harvesting more land than the base model. Since the plant location would be in the Northwest region most of the land harvested would be in the Northwest and Southwest regions (Figure 29). Figure 30 and Figure 32 show that mixed native grasses and native tall grass will dominate the types of grasses harvested and the land under each grass harvested. The tons of biomass harvested in each month are not significantly different between the base model and 50% HD model (Figure 31). At on-site storage facility, the 50% reduced harvest days model stores slightly more biomass feedstock than the base model (Figure 34).

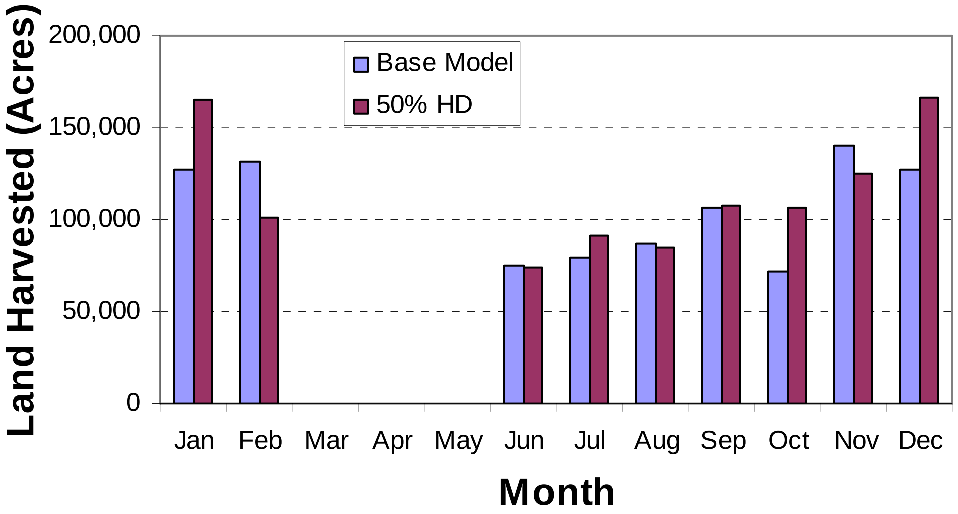


**Figure 28.** **Total number of acres harvested from all supplying counties in each month for the base model and 50% HD model**

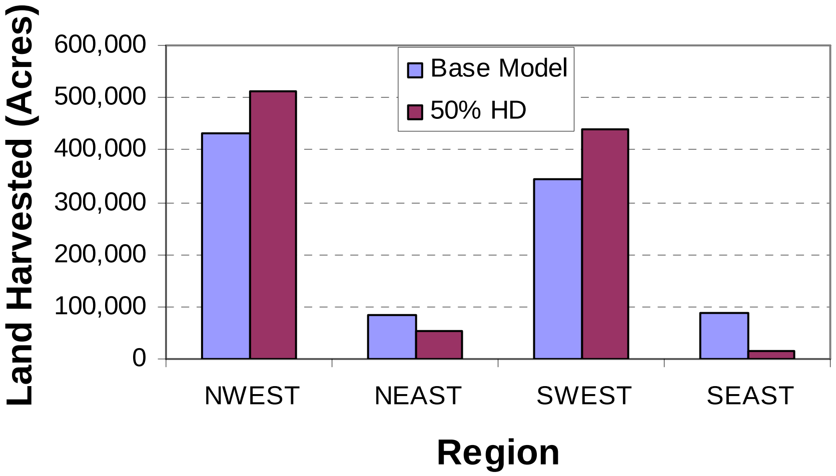


**Figure 29.** **Total number of acres harvested from all supplying counties in each region for the base model and 50% HD model**

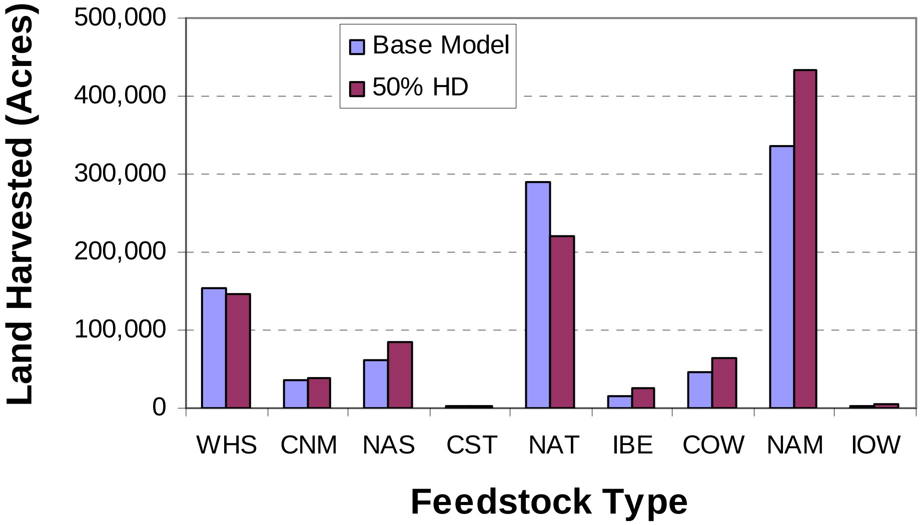


**Figure 30.** **Total number of acres harvested from all supplying counties by biomass feedstock type for the base model and 50% HD model**

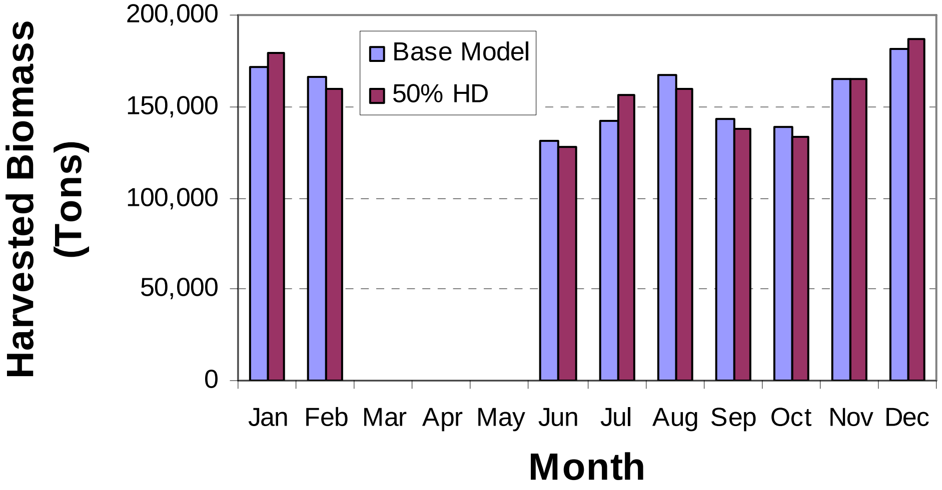


**Figure 31.** **Total dry tons of biomass harvested from all supplying counties in each month for the base model and 50% HD model**

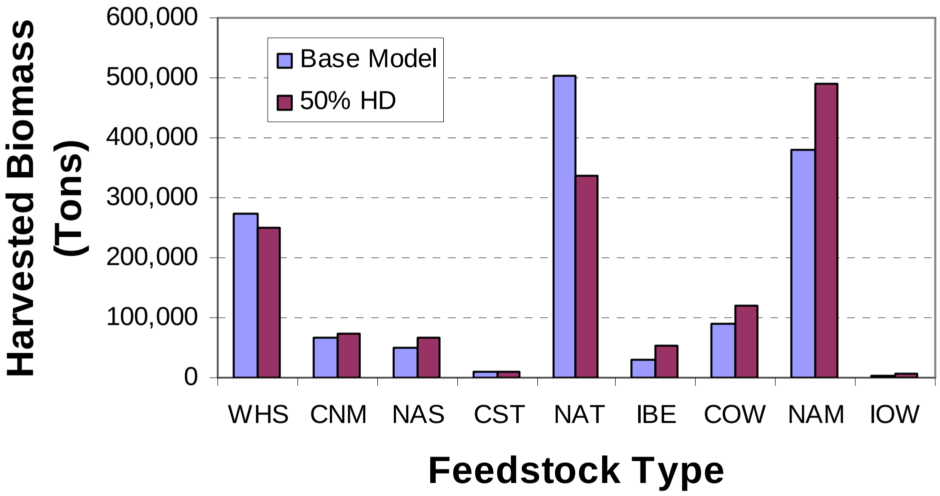


**Figure 32.** **Total dry tons of harvested biomass feedstock from all supplying counties by biomass feedstock type for both the base model and 50% HD model**

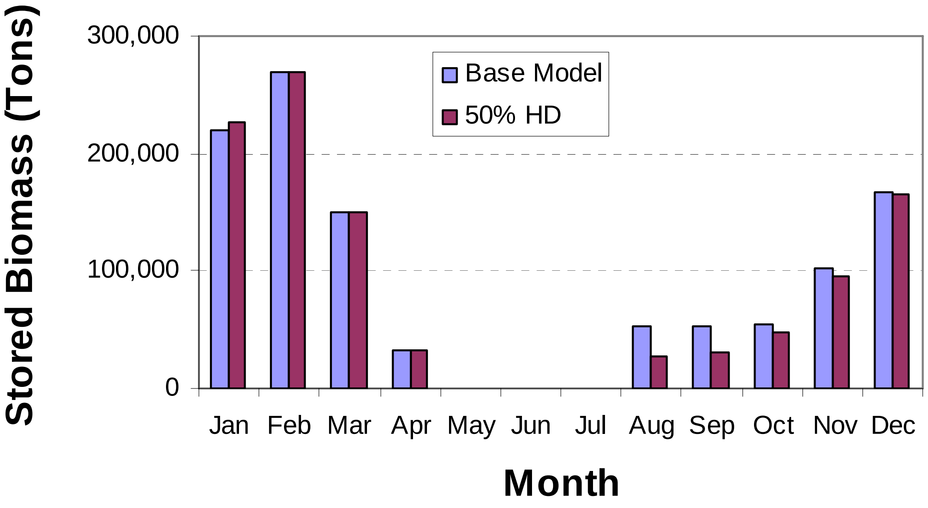


**Figure 33.** **Total dry tons of stored biomass feedstock from all in-field storage facilities in each month for both the base model and 50% HD model**

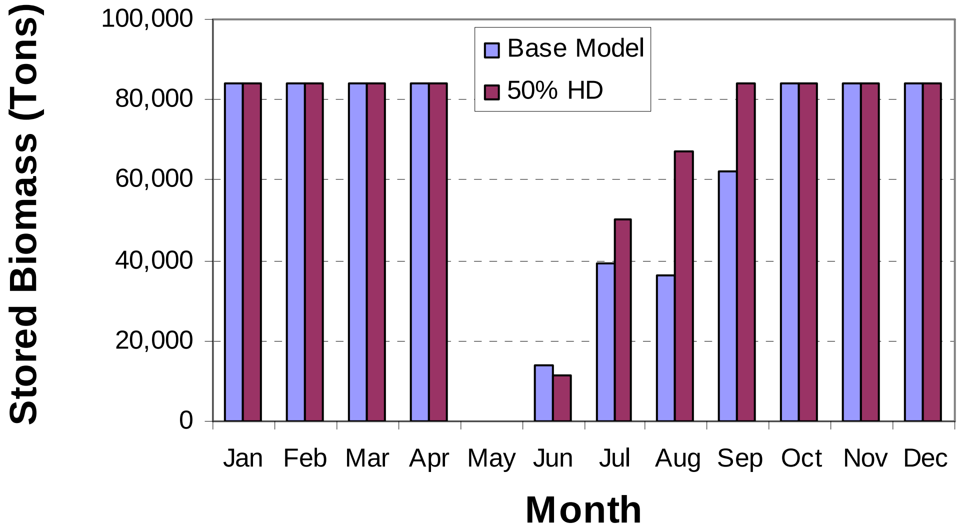


**Figure 34.** Total dry tons of stored biomass feedstock at on-site storage facilities in each month for both the base model and 50% HD model

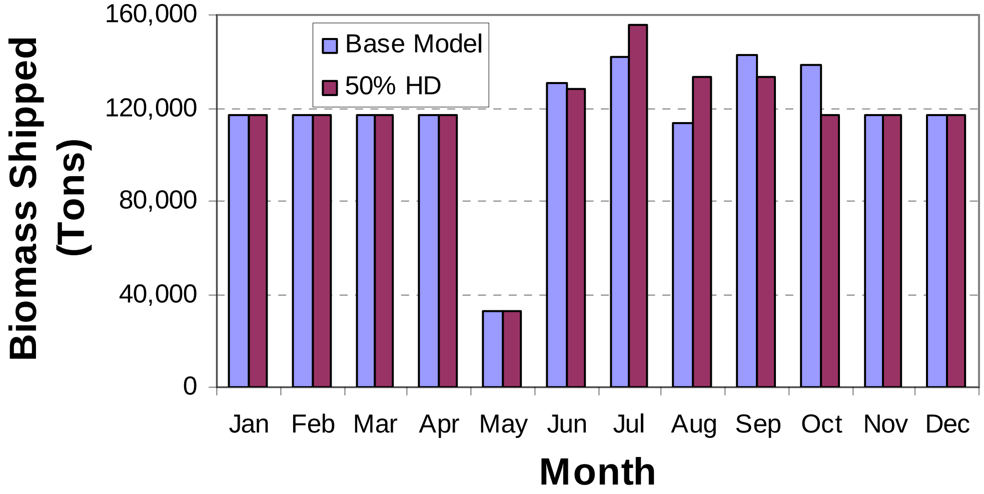


**Figure 35.** Total dry tons of biomass feedstock shipments from the supplying counties to the biorefinery in each month for both the base model and 50% HD model

## Sensitivity Analysis 3: Increased Cost of a Harvest Unit by 50%

Figure 36 through Figure 43 present the comparisons between the base model results and those of the model in which the cost of the harvest unit was increased by 50%. In spite of the slight differences in actual numbers of acres and tons harvested the figures show the same trend in the comparisons between the results from the base model and those from the 150% CHU. Figure 36 and Figure 37 show that the 150% CHU model harvests slightly more acres of biomass than the base model. In both cases most of the acres are harvested in the Northwest and Southwest regions of Oklahoma ( Figure 37). In the Northeast and Southeast regions the base model harvests more acres than the 150% CHU model. The Northeast and Southeast regions have more acres under native tall prairies compared to other regions. The base model harvests more native tall grass than the 150% CHU model, which harvests more acres under native mixed grasses (Figure 38).

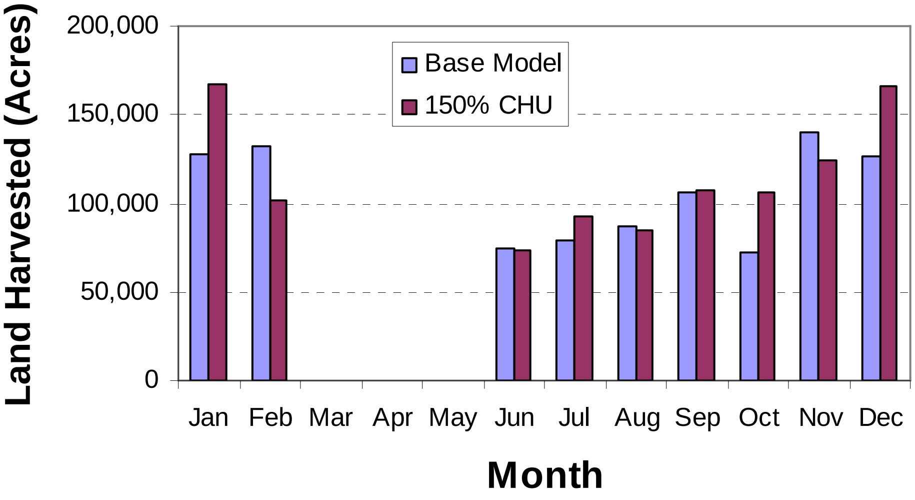


**Figure 36. Total number of acres harvested from all supplying counties in each month for the base model and 150% CHU model**

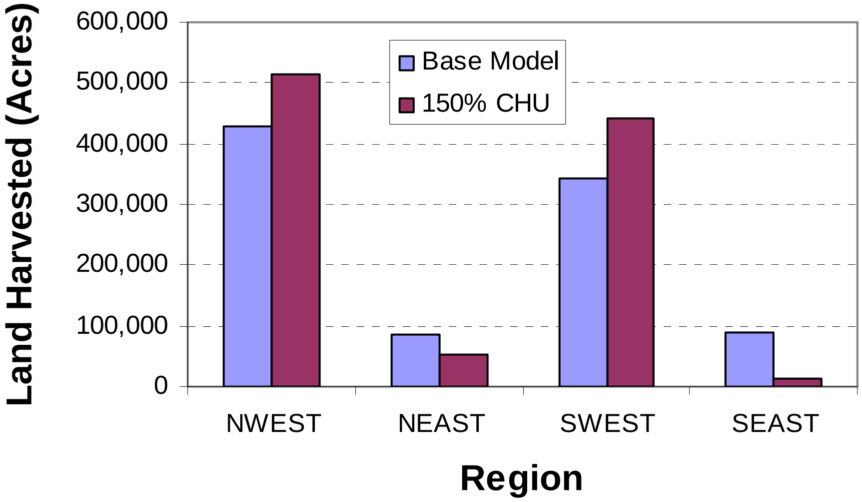


**Figure 37.** **Total number of acres harvested from all supplying counties in each region for the base model and 150% CHU model**

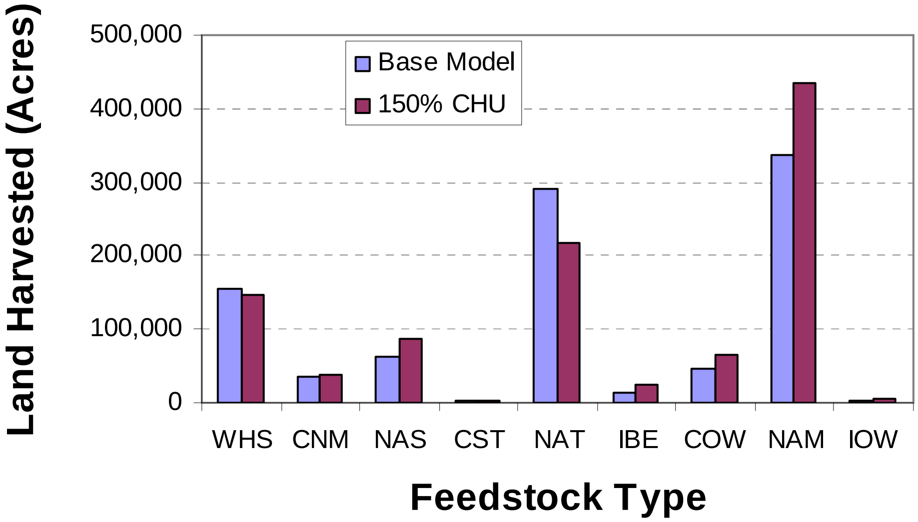


**Figure 38.** **Total number of acres harvested from all supplying counties by biomass feedstock type for the base model and 150% CHU model**

The amount of tons of biomass harvested by month for both the base model and the 150% CHU model are not significantly different (Figure 39). The base model harvests more tons of native tall grass and slightly more wheat straw than the 150% CHU model (Figure 40). The sensitivity analysis model, however, harvests more tons under mixed native prairies than the base model. The 150% CHU model also harvests more tons under the CRP (with old world bluestem, COW, and mixed native grass, CNM) than the base model (Figure 40).

Figure 41 shows that the storage pattern in the field is not significantly different between the two models. The base model stores slightly more biomass in August and September than the 150% CHU model. On the other hand, the 150% CHU model stores more biomass at on-site storage between July and September. Figure 43 is a chart showing the monthly shipments to the biorefinery plant for both models.

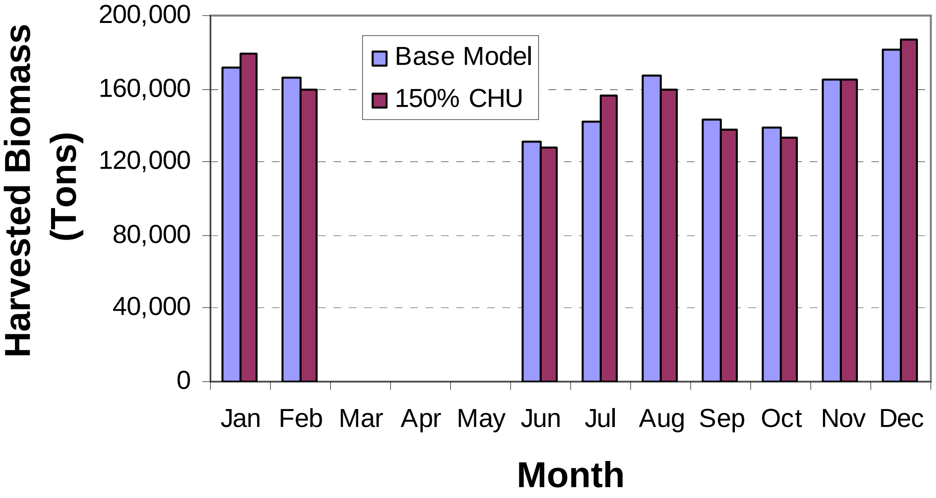


**Figure 39. Total dry tons of biomass harvested from all supplying counties in each month for the base model and 150% CHU model**

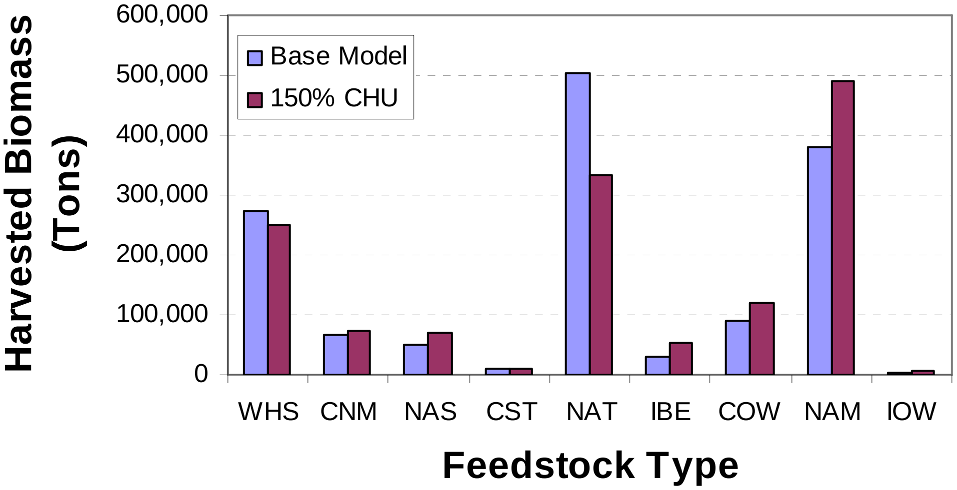


Figure 40. Total dry tons of harvested biomass feedstock from all supplying counties by biomass feedstock type for both the base model and 150% CHU model

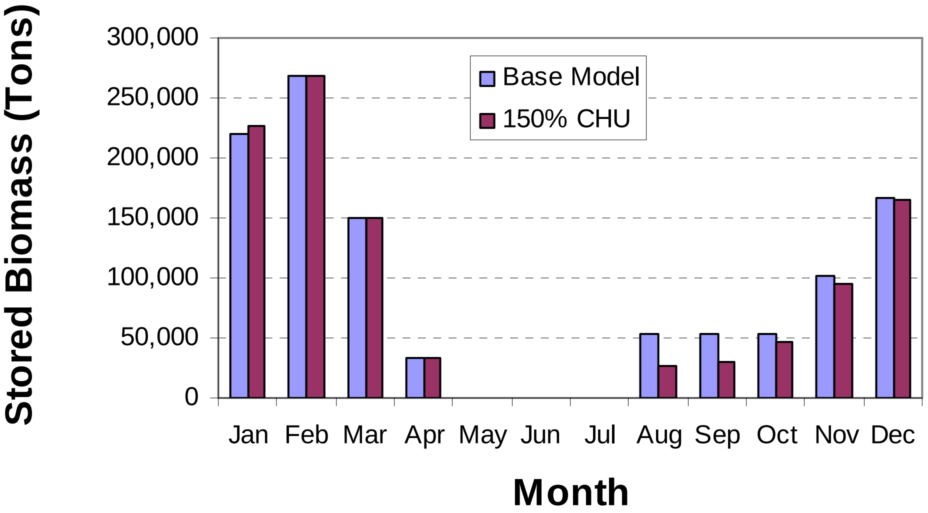


Figure 41. Total dry tons of stored biomass feedstock from all in-field storage facilities in each month for both the base model and 150% CHU model

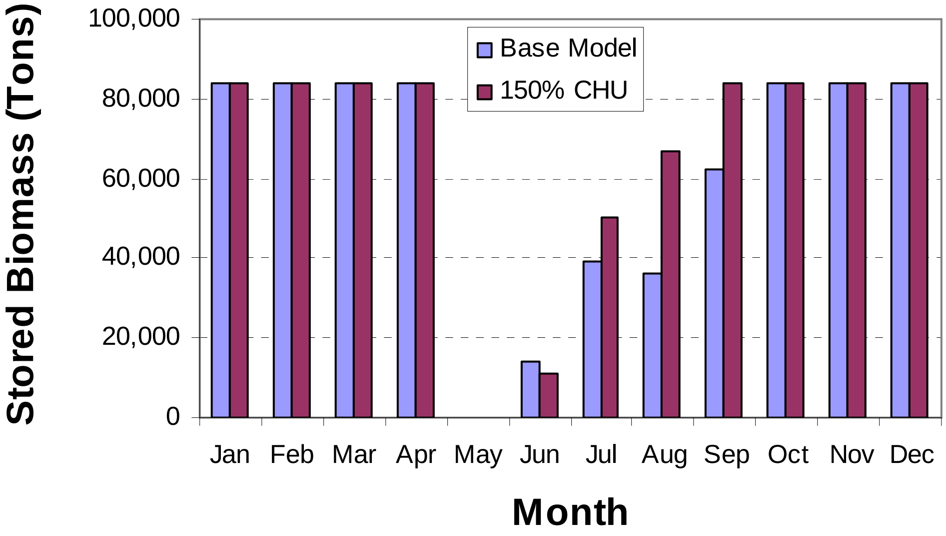


**Figure 42.** **Total dry tons of stored biomass feedstock at on-site storage facilities in each month for both the base model and 150% CHU model**

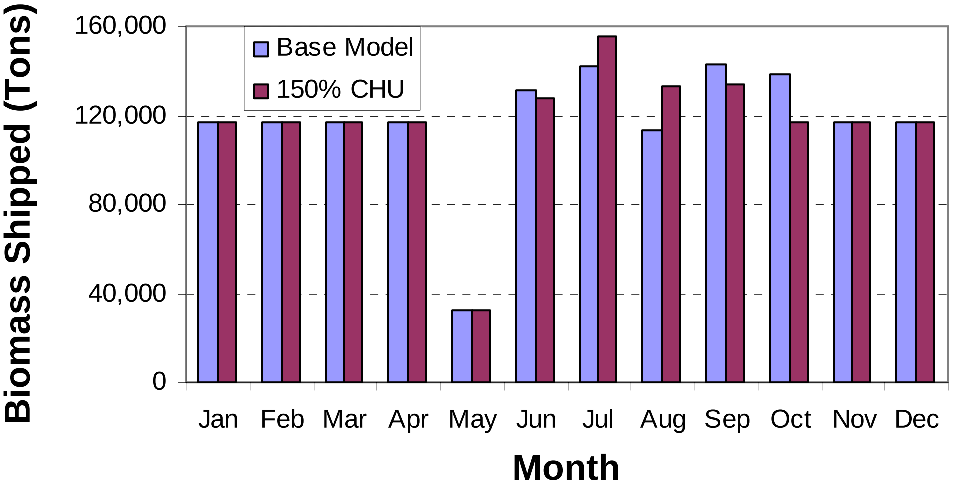


**Figure 43.** **Total dry tons of biomass feedstock shipments from the supplying counties to the biorefinery in each month for both the base model and 150% CHU model**

## Sensitivity Analysis 4: Increased Proportion of Harvested Acres by 25%

Figures 44 through 46 present charts showing the acres of land harvested by the base model versus the sensitivity analysis in which the proportion of harvested acres were increased by 25%. Figure 44 shows that in each month the acres harvested by the sensitivity analysis were more than those harvested by the base model. The sensitivity analysis harvested a lot more acres in the months of December through February the following year. Figure 45 shows that the sensitivity analysis harvested most its required acres in the Northwest and a little in Panhandle and Southwest regions of Oklahoma. The base model harvested most of its required acres in both Northwest and Southwest regions. In Figure 46, it is clear that both models harvested more acres with native prairie grasses followed by wheat straw than any other biomass species. The sensitivity analysis harvested more acres under mixed native grasses followed by native short and wheat straw while the base model harvested more acres under mixed and tall native grasses.

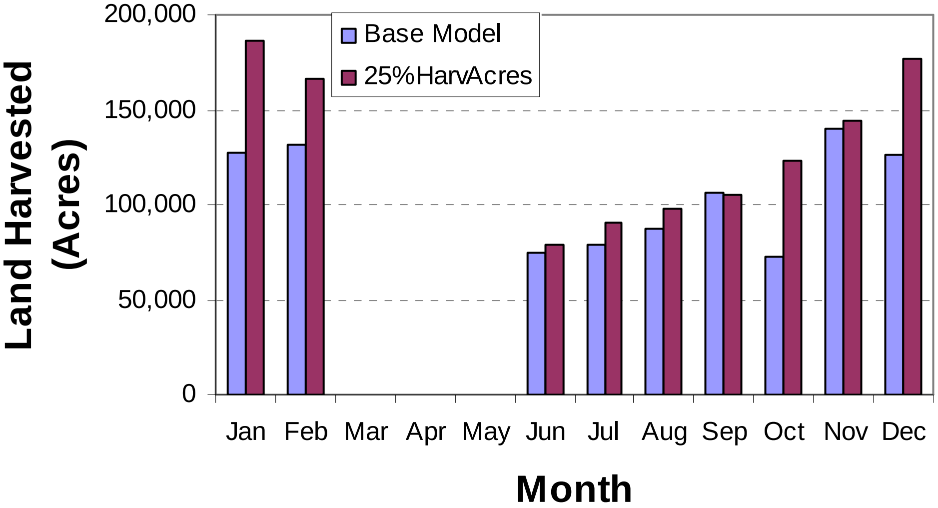


**Figure 44. Total number of acres harvested from all supplying counties in each month for the base model and 25%harvacres model**

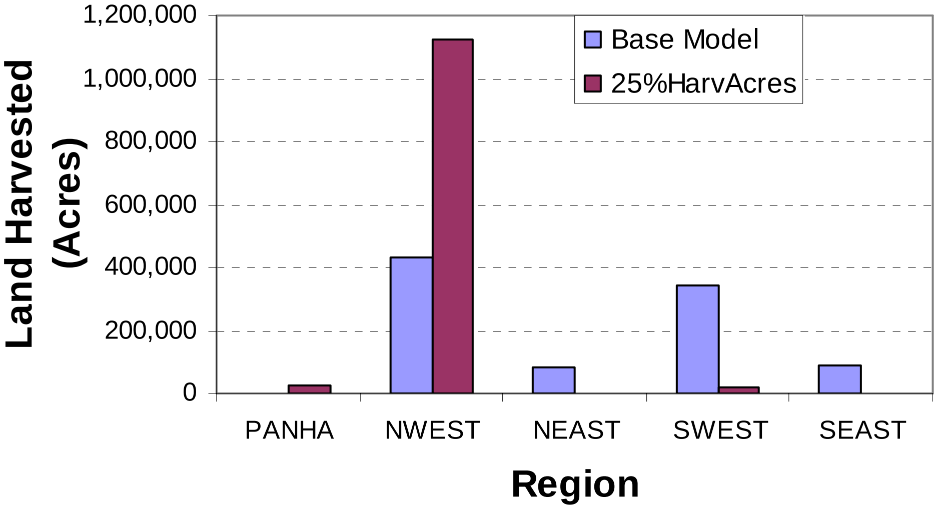


**Figure 45.** **Total number of acres harvested from all supplying counties in each region for the base model and 25%harvacres model**

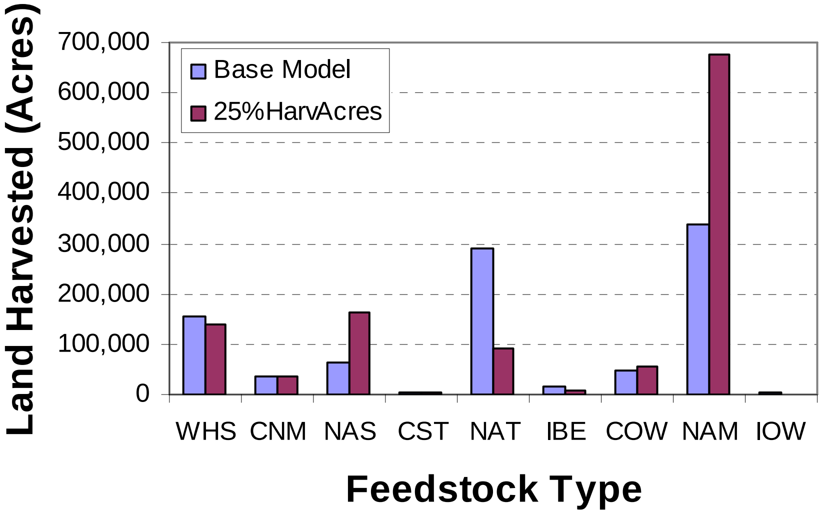


**Figure 46.** **Total number of acres harvested from all supplying counties by biomass feedstock type for the base model and 25%harvacres model**

There is no significant differences between the tons of LCB feedstock harvested in each month for the base model and the sensitivity analysis (Figure 47). However, the sensitivity analysis model harvests a large quantity of mixed native prairie grasses compared to the base model (Figure 48). The base model harvests large quantities of native tall grass followed by mixed native grasses and wheat straw. The second preferred biomass species by the sensitivity model is wheat straw followed by native short and native tall and then old world bluestem grown on CRP land.

Figure 49 is chart showing storage inventory in in-field storage. For in-field storage the base model stores a little more than the sensitivity analysis but this difference is not significant. At the biorefinery the sensitivity analysis model stores more biomass than the base model (Figure 50). Shipments of biomass feedstock from the field and field storage to the biorefinery are almost the same for both the base model and the model with 25% harvested acres (Figure 51).

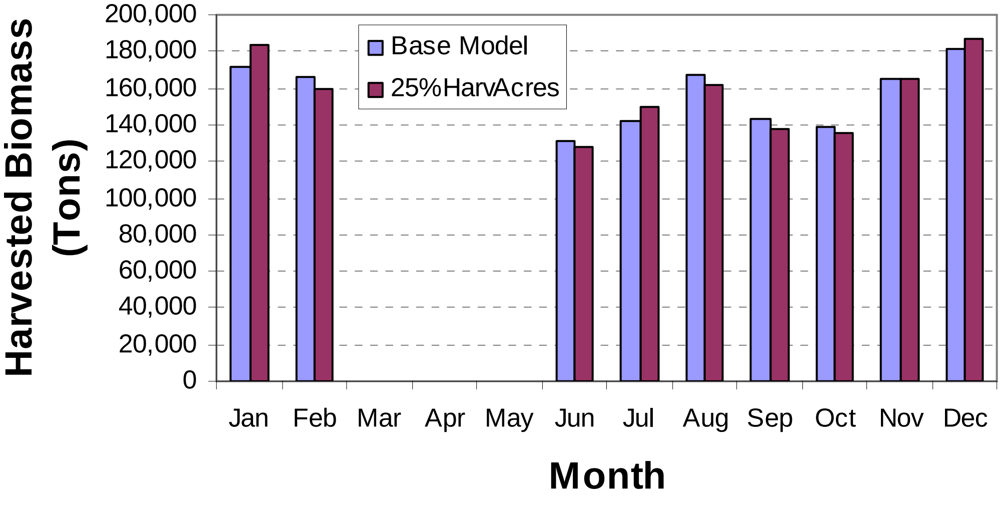


**Figure 47. Total dry tons of biomass harvested from all supplying counties in each month for the base model and 25%harvacres model**

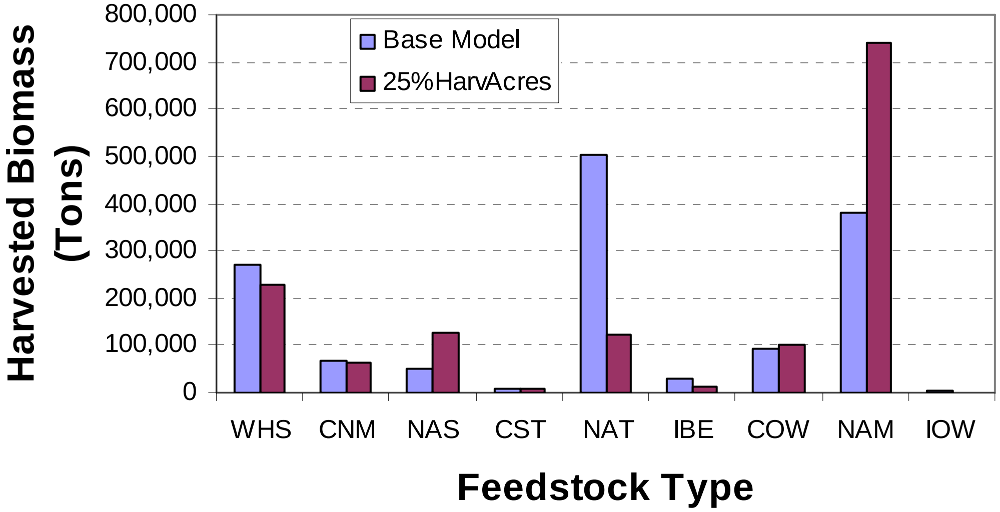


**Figure 48.** **Total dry tons of harvested biomass feedstock from all supplying counties by biomass feedstock type for both the base model and 25%harvacres model**

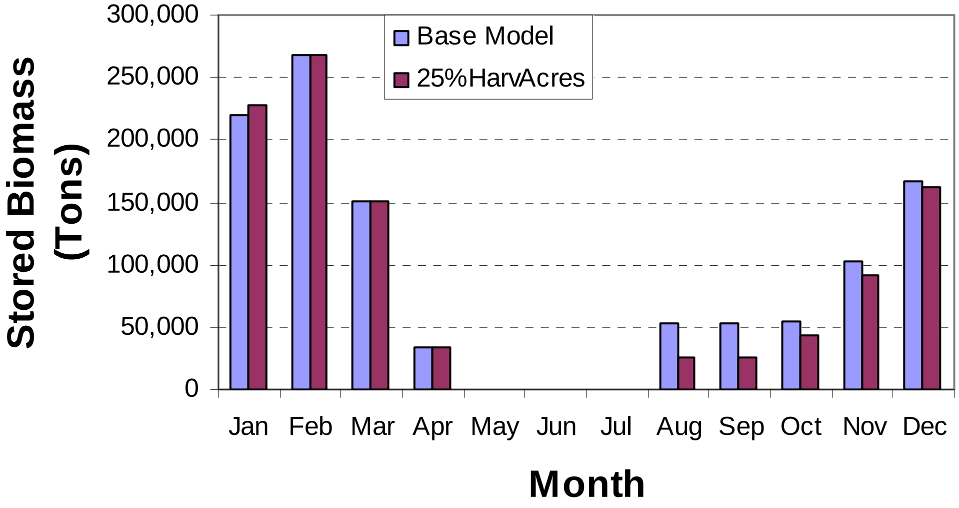


**Figure 49.** **Total dry tons of stored biomass feedstock at on-site storage facilities in each month for both the base model and 25%harvacres model**

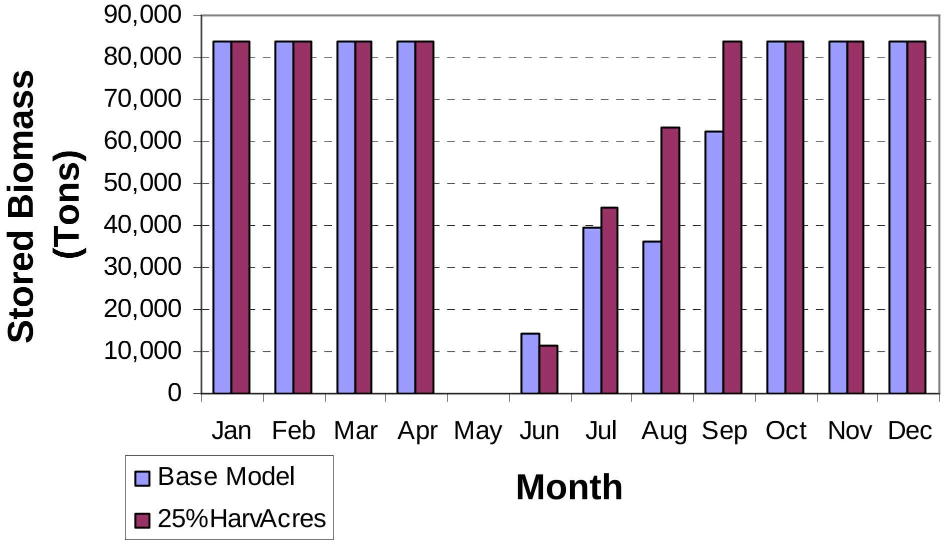


Figure 50. **Total dry tons of stored biomass feedstock at on-site storage facilities in each month for both the base model and 25%harvacres model**

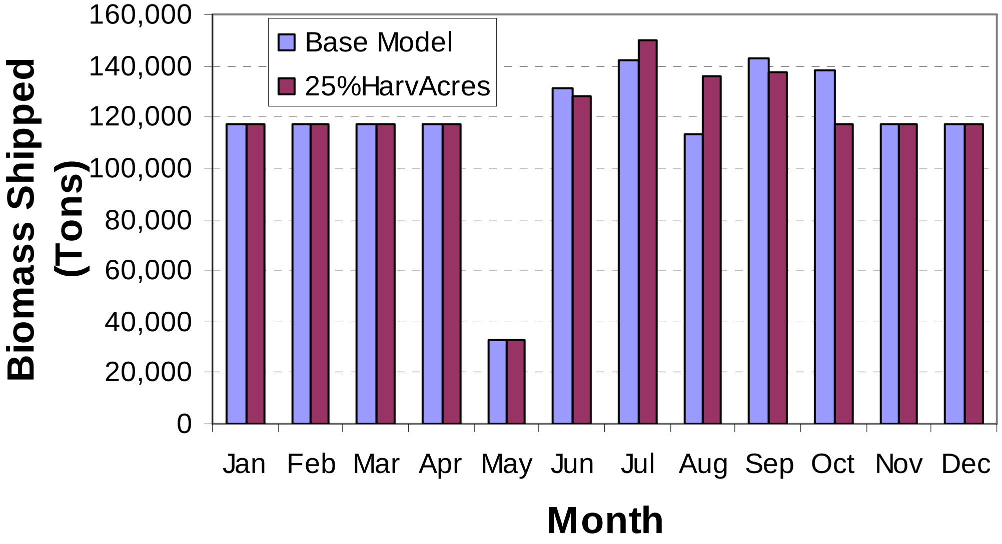


Figure 51. **Total dry tons of biomass feedstock shipments from the supplying counties to the biorefinery in each month for both the base model and 25%harvacres model**

## Sensitivity Analysis 5: Increased Proportion of Harvested Acres by 35%

Figures 52 through 54 present charts showing the acres of land harvested by the base model versus the sensitivity analysis in which the proportion of harvested acres were increased by 35%. Figure 52 shows that the sensitivity analysis harvests more acres of LCB than the base model in the months of October, December, January and February. Figure 53 shows that the sensitivity analysis harvested most its required acres in the Northwest and Panhandle regions of Oklahoma. The base model harvested most of its required acres in both Northwest and Southwest regions. In Figure 54, for the sensitivity analysis most acres harvested were under mixed native grasses and native short grasses followed by wheat straw while the base model harvested more acres under mixed and tall native grasses.

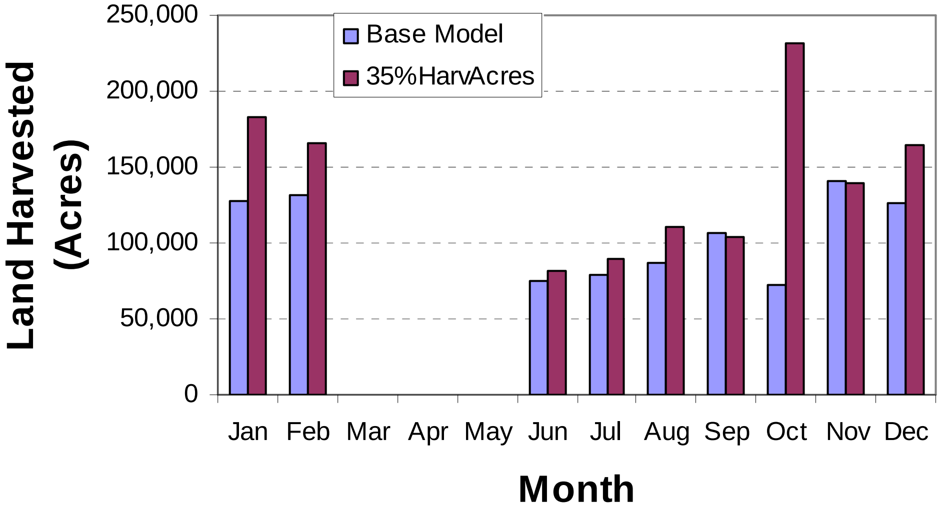


**Figure 52. Total number of acres harvested from all supplying counties in each month for the base model and 35%harvacres model**

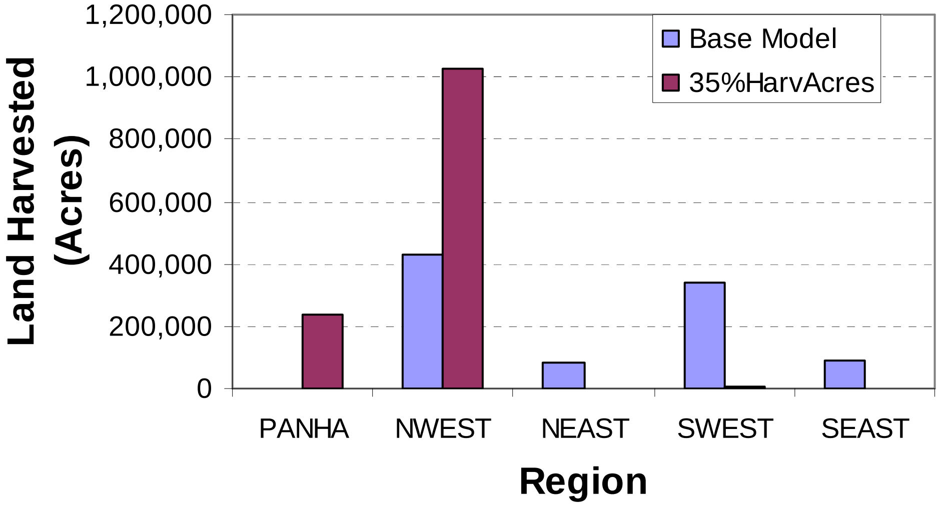


**Figure 53. Total number of acres harvested from all supplying counties in each region for the base model and 35%harvacres model**

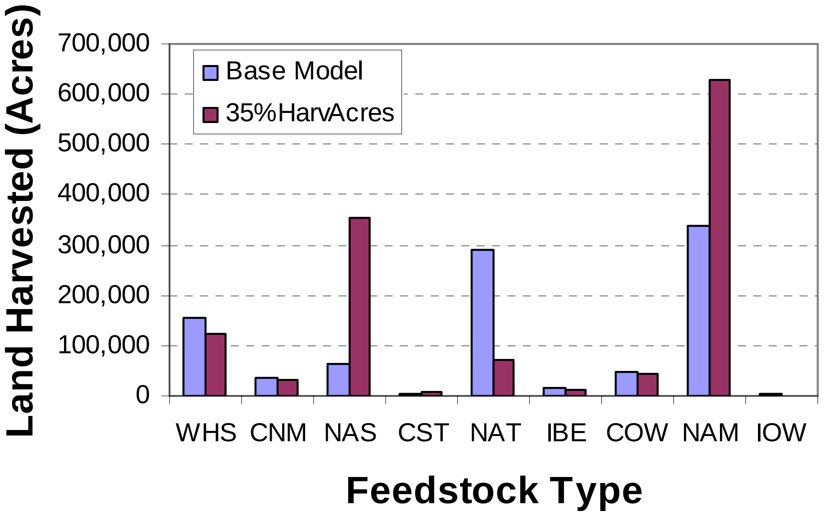


**Figure 54. Total number of acres harvested from all supplying counties by biomass feedstock type for the base model and 35%harvacres model**

There is no significant differences between the tons of LCB feedstock harvested in each month for the base model and the sensitivity analysis (Figure 55). However, the sensitivity analysis model harvests a large quantity of mixed native prairie grasses followed by wheat straw compared to the base model (Figure 56). The base model harvests large quantities of native tall grass followed by mixed native grasses and wheat straw.

Figures 57 and 58 are charts showing storage inventory in in-field storage and in storage facility at the biorefinery. For in-field storage the base model stores a little more than the sensitivity analysis but this difference is not significant. The base model stores more biomass than the sensitivity analysis in the months of August and September. At the biorefinery the sensitivity analysis model stores more biomass than the base model (Figure 58). Shipments of biomass feedstock from the field and field storage to the biorefinery are almost the same for both the base model and the model with 35% harvested acres (Figure 59).

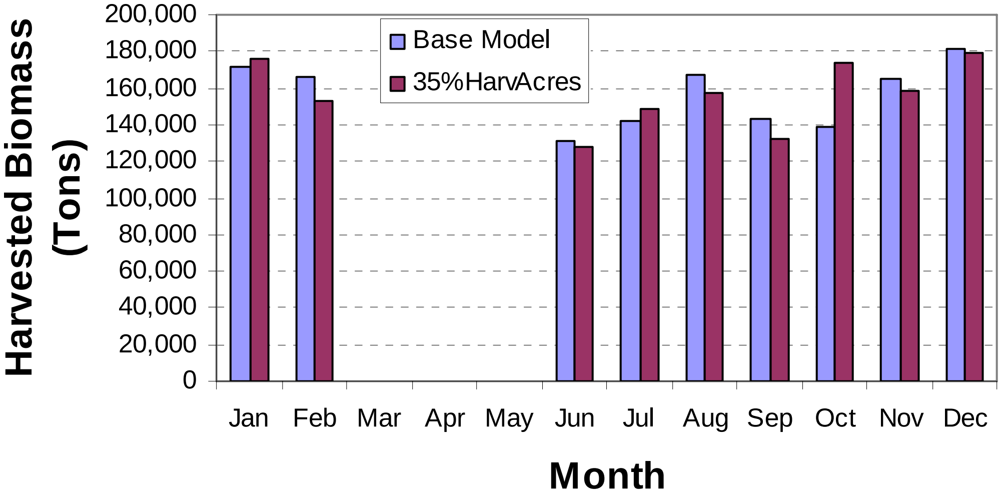


**Figure 55. Total dry tons of biomass harvested from all supplying counties in each month for the base model and 35%harvacres model**

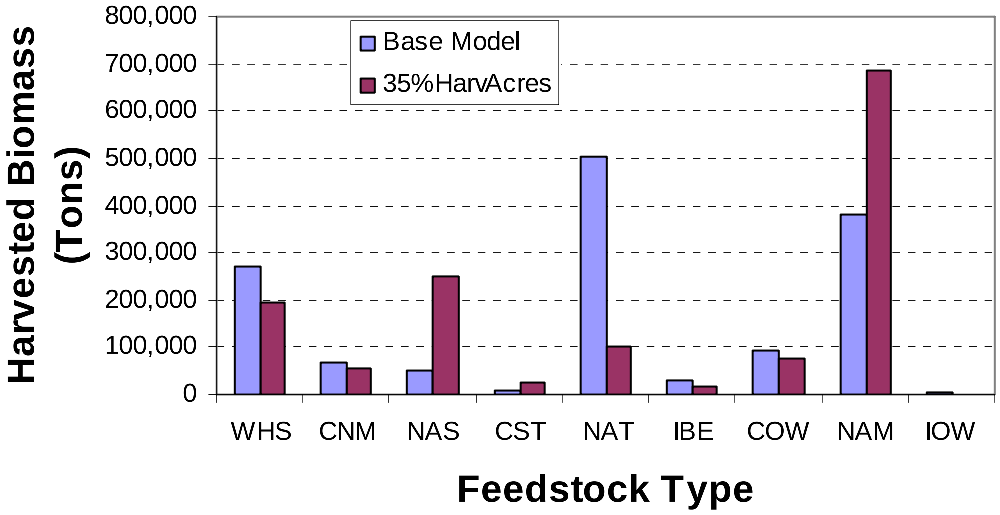


**Figure 56.** **Total dry tons of harvested biomass feedstock from all supplying counties by biomass feedstock type for both the base model and 35%harvacres model**

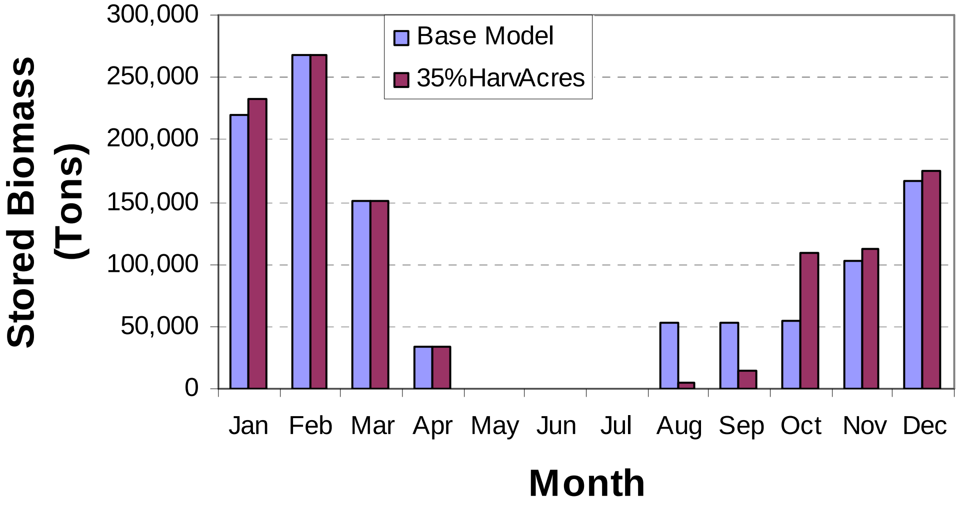


**Figure 57.** **Total dry tons of stored biomass feedstock at on-site storage facilities in each month for both the base model and 35%harvacres model**

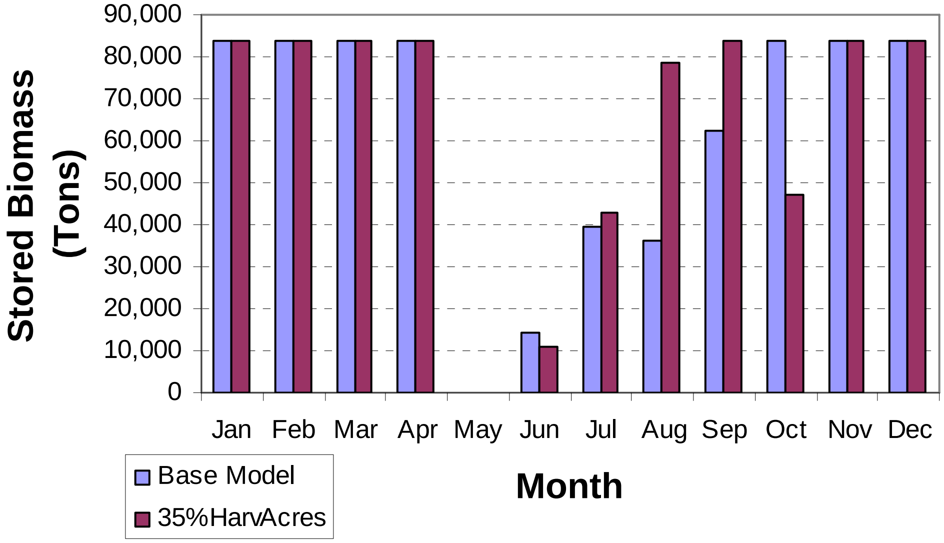


**Figure 58.** **Total dry tons of stored biomass feedstock at on-site storage facilities in each month for both the base model and 35%harvacres model**

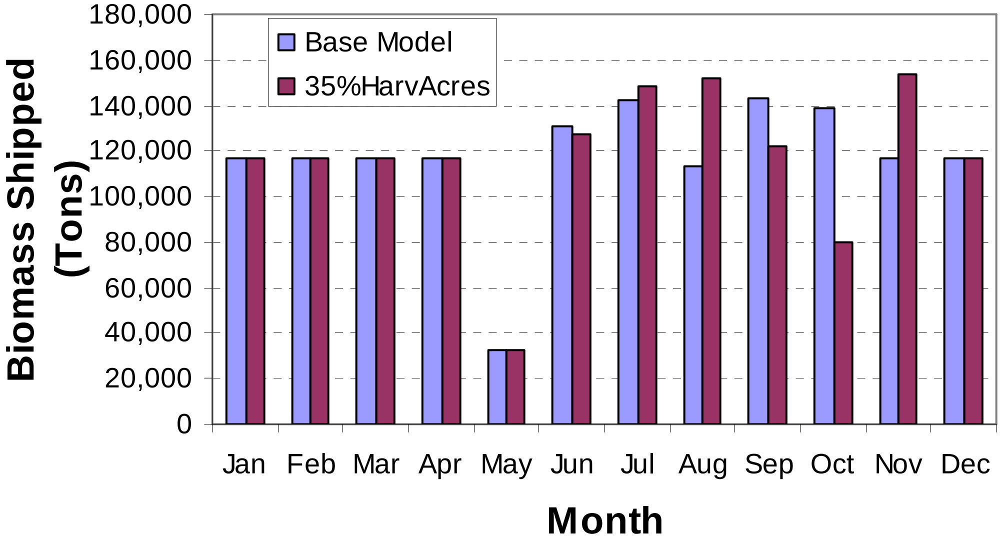


**Figure 59.** **Total dry tons of biomass feedstock shipments from the supplying counties to the biorefinery in each month for both the base model and 35%harvacres model**

## Would Crop Residues Be an Economical Source of Biomass Feedstock

The second objective was to determine the cost to deliver a ton of crop residue (wheat straw or corn stover) to a biorefinery that could process 1,000, 2,000, or 4,000 dry tons per day. To achieve this objective, a GAMS model was developed to solve the base case scenario and three sensitivity analyses. The results for the model and sensitivity analyses are presented in this section.

Table 15 gives a summary of some results for four runs of the crop residue model. The first model was run by assuming all acres (100%) with crop residues would be available for harvesting but only 60% of the tons of residues on each acre would be actually removed. The idea is to have at least 30% of crop residues left on each acre for soil erosion control and enhancement of soil fertility. This model is referred in Table 15 as RES 100-60. Three sensitivity analysis were done by varying some parameters in RES 100-60. The following sensitivity analyses were done: (i) in the first sensitivity analysis (RES 100-40) the assumption is that all crop residues acres would supply crop residues to the biorefinery but only 40 percent of the total tons of biomass on each acre would be harvested leaving 60 percent for soil erosion control; (ii) in the second sensitivity analysis (RES 50-60) the assumption is that only half of the total acres of crop residues would be available to provide crop residues to the biorefinery with 60 percent of the tons of residues being harvested; and (iii) the third sensitivity analysis (RES 25-60) assumes that only 25 percent of the total acres of crop residues would be supplying crop residues to the biorefinery with 60 percent of the tons of residues being harvested.

Table 15 shows that the main cost component to deliver a continuous flow of crop residues to a biorefinery is harvest cost followed by transportation cost. The model RES

**Table 15. Comparison of Results of the Base Model with the Sensitivity Analyses Assuming a Biorefinery That Only Uses Crop Residues as Biomass Feedstock**

| | Model Comparisons | | | |
|---|---|---|---|---|
| Item | RES 100-60 | RES 100-40 | RES 50-60 | RES 25-60 |
| Biomass Acquisition Cost ($/ton) | 10.00 | 10.00 | 10.00 | 10.00 |
| Harvest Cost ($/ton) | 25.69 | 30.28 | 33.36 | 33.36 |
| Field Storage Cost ($/ton) | 1.11 | 1.12 | 1.23 | 1.23 |
| Transportation Cost ($/ton) | 16.97 | 16.17 | 16.36 | 16.36 |
| Total Cost of Delivered Feedstock ($/ton) | 53.77 | 57.58 | 60.94 | 60.94 |
| Net Present Worth ($,000) | 115,249 | 82,687 | 54,301 | 7,509 |
| Harvest Units (Number) | 83 | 98 | 108 | 54 |
| Average Investment in Harvest Machines ($,000) | 48,970 | 57,820 | 63,720 | 31,860 |
| Harvested Acres | 1,153,416 | 1,887,765 | 1,296,806 | 648,403 |
| Total Biomass Harvested (tons) | 1,424,890 | 1,427,478 | 1,428,250 | 714,125 |
| Biomass Processed (tons) | 1,400,000 | 1,400,000 | 1,400,000 | 700,000 |
| Number of Biomass Feedstock Harvested | 2 | 2 | 2 | 2 |
| Average Distance Hauled (miles) | 127 | 120 | 122 | 122 |
| Plant Location | Custer | Custer | Custer | Custer |
| Plant Size | Large | Large | Large | Medium |
| Capacity Usage (%) | 100% | 100% | 100% | 100% |

100-60 incurs a harvest cost of $25.69 per ton which is more than twice higher than the harvest cost in the base model of $10.72 per ton (Table 12). Compared to the base model which had a transportation cost of $14.15 per ton the RES 100-60 model transports a ton of residues at a cost of about $17.00. In general all costs per ton of biomass are higher when the model is restricted to use crop residues only as the sole feedstock for a biorefinery than when a variety of biomass feedstock is considered as in the base model. The expected total costs to deliver crop residues as biorefinery feedstock for the crop residue model (RES 100-60) is $53.77 per ton. Compared to the expected total cost of delivered feedstock of $35.37 achieved by the base model, the RES 100-60 model delivers a ton of feedstock to a biorefinery at about $18.00 per ton more than the base model. Ho (1985b) found that use of crop residue for conversion to biogas in New York State was uneconomical. Gallagher et al. reported that due to the diversity of growing conditions, conservation requirements, and forage demands in the Great Plains the cost to deliver a ton of crop residues was wider than in other regions of U.S.A. On the other hand, studies on the economics of using crop residues as biorefinery feedstock done in the corn belt have reported lower cost to deliver a ton of biomass than this study. The large concentration of feedstock in the corn belt enables procurement of feedstock at lower prices and from shorter distances. The other reasons some studies have reported lower cost to deliver a ton of crop residues as feedstock to a biorefinery than this study are assumptions about harvest, storage and transportation costs. These variables have varied among different studies.

Using crop residues only as a biorefinery feedstock would be uneconomical due to two reasons. Firstly, while the base model considers a variety of feedstock ranging from crop residues, native grasses and improved pastures, the crop residue model assumes only two types of feedstock, thus wheat straw and corn stover. By restricting the model to two feedstock types neglecting some types that may be cheaper to procure this results in higher per ton procurement and transportation costs. Secondly, since the crop residue model is restricted to crop residues it is therefore restricted to a harvest season of a few months compared to the base model, which has a longer harvest season. To harvest enough biomass in a restricted harvest season requires more harvest machinery, hence, higher harvest cost than an unrestricted harvest season. Furthermore, by harvesting a large quantity of biomass in a short period and storing it for the whole year to supply the biorefinery results in higher storage costs. Consequently, the crop residue model (RES 100-60) has a higher expected cost to deliver a ton of LCB feedstock than the base model with a variety of LCB feedstock harvested for a longer harvest season.

RES 100-60 model optimally selects 83 harvest units at an average investment of \$48.97 million. 1,153,416 acres of land are harvested supplying a total of 1,424,890 dry tons of biomass. Biomass feedstock is hauled an average of 127 miles radius from the field to the plant. The plant is used at 100 percent capacity.

Table 15 also gives the comparisons of results of the RES 100-60 model versus model sensitivity analyses that were done. The RES 100-60 model assumes that all acres with crop residues will be supplying biomass feedstock to the biorefinery but only 60 percent of the residues would be removed leaving 40 percent to comply with USDA's requirements for soil erosion control. In other words, it assumes that all farmers producing crop residues would be willing and able to sell their crop residues to the biorefinery. RES 100-40 shows that by harvesting only 40 percent of biomass versus 60 percent (RES 100-60) harvest cost per ton increases thereby increasing the total cost of delivered feedstock from $53.77 per ton in RES 100-60 model to $57.58 per ton in RES 100-40. Since only a small proportion of biomass quantity can be harvested compared to RES 100-60, RES 100-40 harvests more acres than RES 100-60 even though the total tons harvested are almost the same. This is because by accessing only 40 percent of the biomass feedstock available more land would be needed to supply the same amount of feedstock required by the biorefinery. To harvest this land, RES 100-40 optimally selects 15 more harvest units than RES 100-60 model. This raises the average investment cost in harvest machines from $48.97 million in RES 100-60 to $57.82 million in RES 100-40. Biomass feedstock is hauled from less distance than the base case scenario (i.e. 120 miles radius versus 127 miles radius) resulting in a slightly less transportation cost per ton (Table 15).

In the case of RES 50-60, by assuming that half of the acres are supplying biomass feedstock the model selects 108 harvest units (Table 15) at an average investment of $63.72 million, which is $14.75 million greater than RES 100-60 scenario. With less acres available more harvest units are required to achieve the same job. The higher number of harvest units result in higher harvest cost in RES 50-60 ($33.36) than in RES 100-60 scenario ($25.69). The higher harvest cost result in an increase in the total cost of delivered ton of biomass feedstock from RES 100-60 scenario by $7.17 per ton. Biomass feedstock is hauled from less distance than RES 100-60 scenario (i.e. 122 miles radius versus 127 miles radius) resulting in a less transportation cost per ton of biomass (Table 15).

RES 100-60 scenario is very sensitive to the number of acres that would be supplying biomass feedstock to the biorefinery plant. If only 25 percent of the acres under crop residues would be available for harvesting of biomass assuming 40 percent of the tonnage available on land is left for soil erosion control (RES 25-60), then there would not be sufficient feedstock material to sustain a large plant. Therefore the model optimally selects a medium plant that is used at 100% (Table 15). The per ton total cost of delivered feedstock is higher in RES 25-60 because the per ton harvest cost and transportation cost are higher.

## Graphical Analysis: The Crop Residue Model and Sensitivity Analyses

### The Crop Residue Model (RES 100-60)

Figure 60 presents the number of acres harvested by months. Crop residues can only be harvested in the months of June and July for wheat straw, and September and October for corn stover. In those months the yield adjustment factor is equal to one and zero for all other months (Table 8). This is because crop residues can only be harvested in the months when grain has been harvested and before land preparation begins for the next crop. Figure 60 shows that, in total, more land is harvested in the months of June and July than in September and October. This is because in the months of June and July only wheat straw can be harvested and there are more wheat straw acres in Northwest region of Oklahoma where the model locates the plant. Figure 61 gives evidence that most of these harvested acres are in the Southwest and Northwest regions. This is consistent with optimal plant location for this model, which is Custer county in the

Northwest. Very little land is harvested in the Northeast and Southeast regions of Oklahoma. Since only wheat straw can be harvested in the months of June and July,

Figure 62 shows that most acres harvested in those months are under wheat straw. In the state of Oklahoma average yields for corn stover are higher than those for wheat straw. However, more land in the state is allocated to wheat than corn. For the period 1999-2003, in the Northwest and Southwest regions, about 3,224,280 wheat acres were harvested annually versus 40,980 corn acres. However, the average yields of corn stover were higher than those of wheat straw (i.e. 5,531 lbs per acre for corn stover versus 3,354 lbs per acre for wheat straw). Figure 63 gives the total tons of wheat straw and corn stover harvested from supplying counties and Figure 64 shows that most of the tons harvested would be harvested in the months of June and July. Therefore, most of the biomass feedstock processed at the biorefinery would be wheat straw.

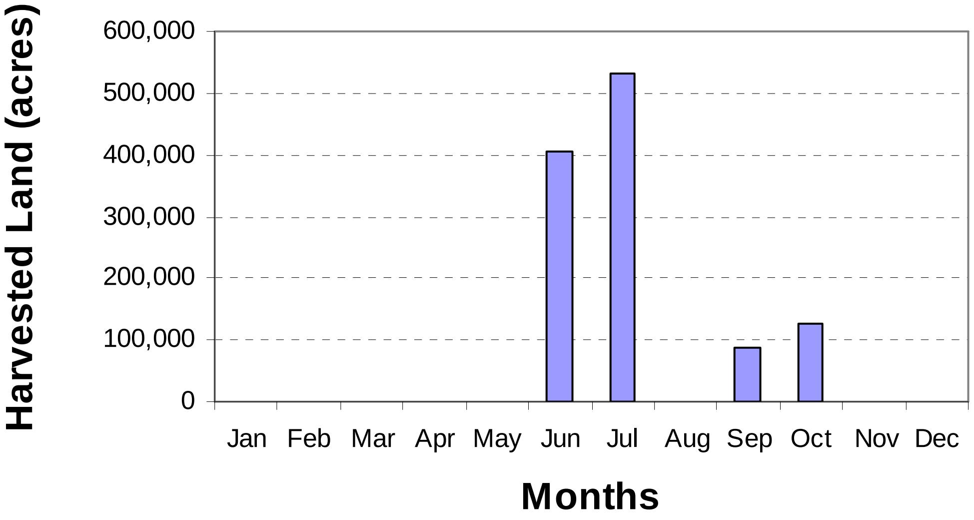


**Figure 60. Total number of acres harvested from all crop residues supplying counties by month for the RES 100-60 scenario of the crop residue model**

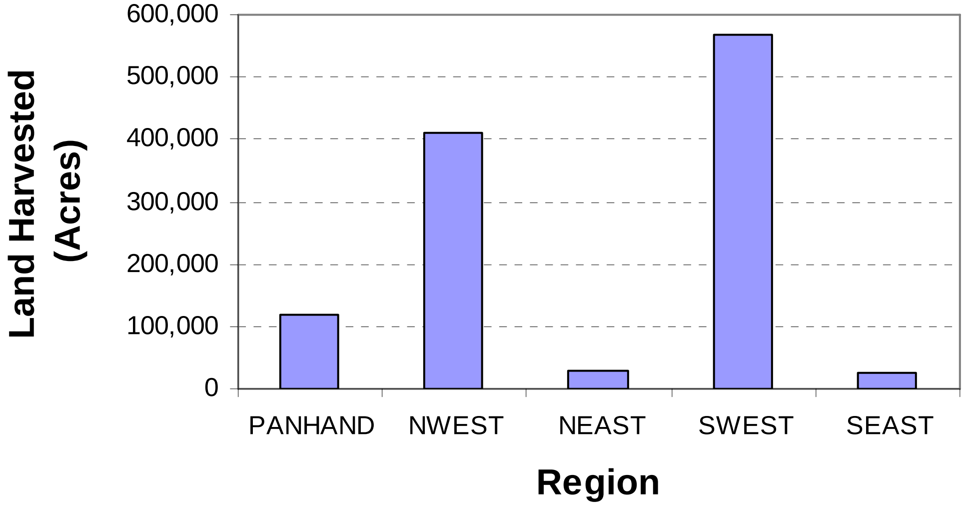


**Figure 61. Total number of acres harvested from all supplying counties in each region for the RES 100-60 scenario of the crop residue model**

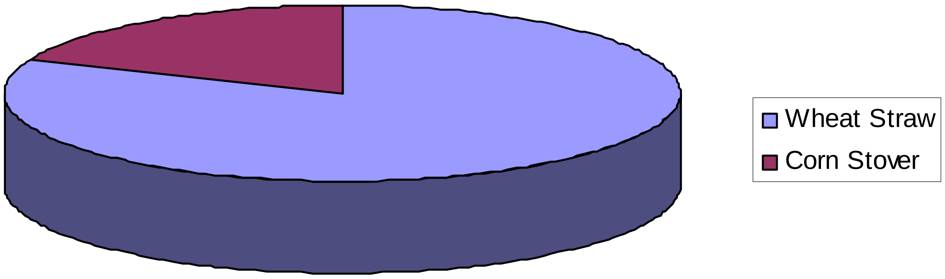


**Figure 62. Total number of acres harvested from all supplying counties by biomass feedstock type for the RES 100-60 scenario of the crop residue model**

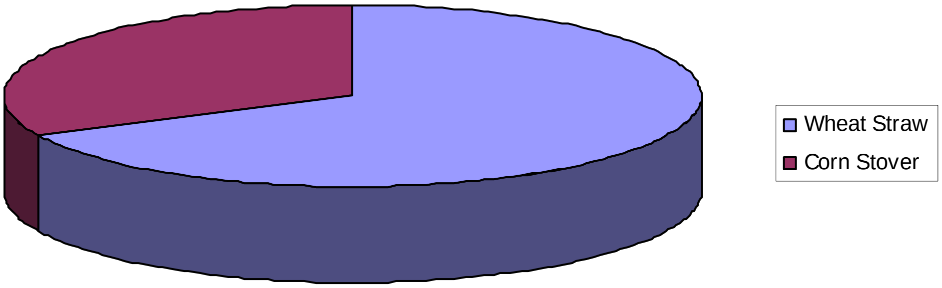


Figure 63. Total tons of biomass harvested from all supplying counties by biomass feedstock type for the RES 100-60 scenario of the crop residue model

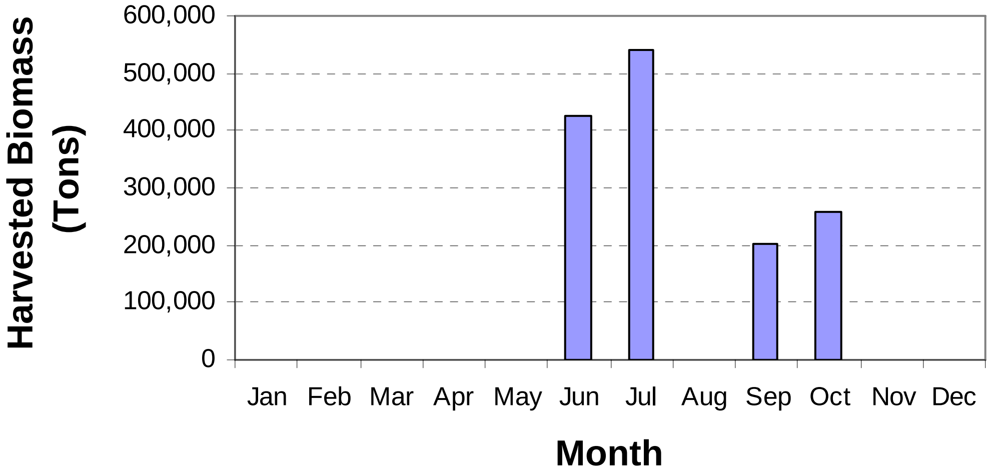


Figure 64. Total dry tons of biomass harvested from all supplying counties by month for the RES 100-60 scenario of the crop residue model

## Post-Harvest Activities

Figure 65 presents the tons of crop residues stored in the field in each month for the base case scenario. Replenishment of in-field storage reserves starts with the month of June when wheat straw is harvested. In the month of July storage inventory rises to more than twice as much as June inventory. Since there is no biomass harvested in the month of August, some biomass in field storage is shipped to the biorefinery. Together with the biomass in the on-site storage these provide the needed biomass feedstock for biorefinery processing for the month of August. Table 15 shows that RES 100-60 scenario of the crop residue model optimally selects a large plant located in the Custer county, Northwest region. A large biorefinery plant is assumed to process 4,000 dry tons of biomass per day. Assuming 350 operating days per year the large plant would process 1,400,000 dry tons of biomass per year, which is about 1,400,000 dry tons/year ÷ 12 months/year = 116,667 dry tons of biomass per month. Figure 64 shows that harvesting of crop residues resumes in the month of September and continues through the month of October. During this period the crop residue harvested is corn stover.

Since October is the last month harvesting is done, at the end of October storage inventory both in the field storage and on-site storage must have sufficient biomass feedstock to last until June the following year when harvesting resumes (Figure 65). At the end of the month of April 32,915 dry tons of biomass are in the in-field storage (Figure 65) and the on-site storage is at the maximum capacity i.e. 84,000 tons of biomass (Figure 66). The maximum storage capacity at the biorefinery plant of any size was set at three weeks times the daily processing capacity of the plant. For a large biorefinery plant (a plant with processing capacity of 4,000 dry tons biomass per day), on-site storage capacity would be 4,000 dry tons/day × 21 days = 84,000 dry tons. Storage losses at in-field storage were set at 0.5% per month, therefore the 32,915 dry tons in in-field storage at the end of April would be 32,915 dry tons × 0.995 = 32,751dry tons in May, which would be shipped to the biorefinery in the month of May since there is no harvesting of biomass done in that month (Figure 67).

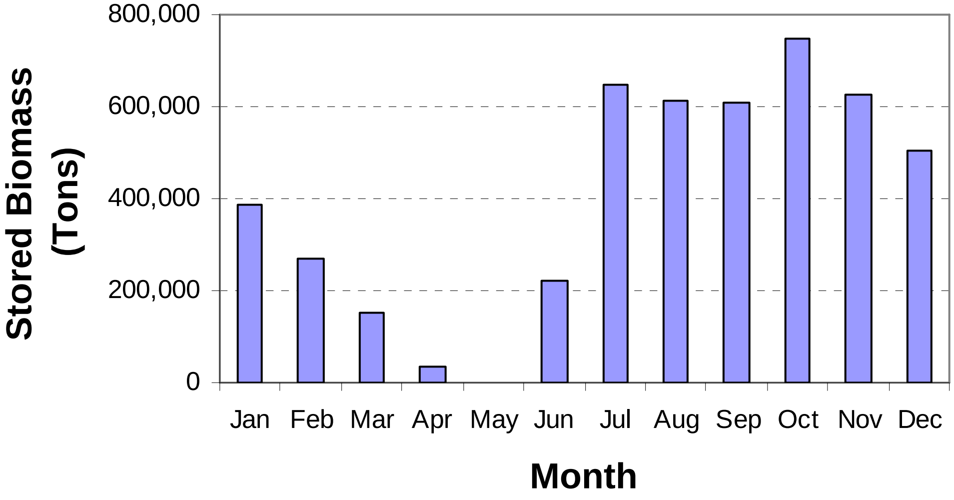


**Figure 65. Total dry tons of stored biomass feedstock from all in-field storage facilities in each month for the RES 100-60 scenario of the crop residue model**

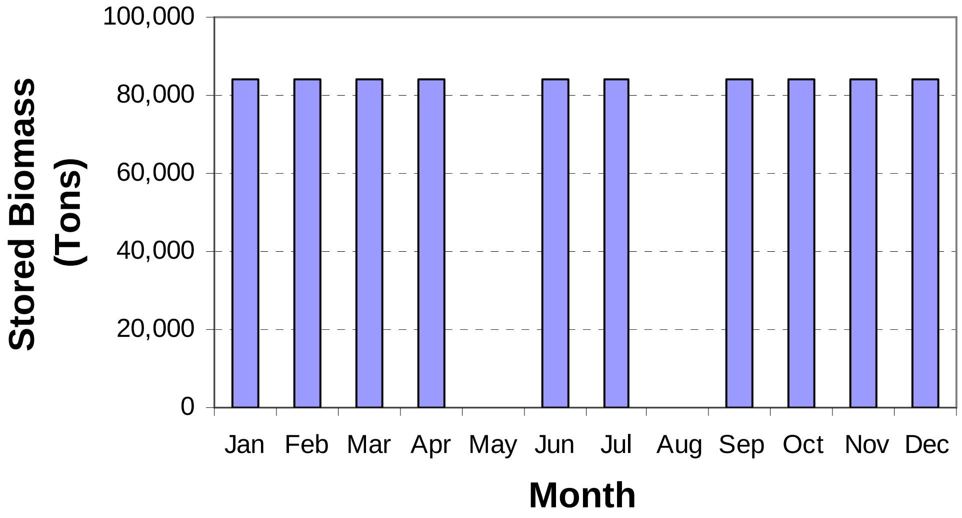


**Figure 66. Total dry tons of stored biomass feedstock at on-site storage facilities in each month for the RES 100-60 scenario of the crop residue model**

Storage losses at the biorefinery (i.e. on-site storage) were set at 0.1% per month. Therefore 84,000 dry tons in on-site storage at the end of April would be 84,000 × 0.999 = 83,916. Figure 67 shows shipment of 32,751 tons of biomass from in-field storage in May to the biorefinery leaving zero inventories in the month of May in field storage (Figure 65). Adding the 32,751 dry tons shipped to the biorefinery to the 83,916 dry tons already available in the storage at the biorefinery provides the required biomass feedstock for the month of May, i.e. 32,751 dry tons + 83,916 dry tons = 116,667 dry tons. Harvesting resumes in the month of June during which 424,545 dry tons are harvested (Figure 64). Of this amount, 223,878 dry tons are put in field storage (Figure 65) and 200,667 dry tons are shipped to the biorefinery (Figure 67). Of the 200,667 dry tons shipped to the plant, 84,000 dry tons are put in storage in the month of June (Figure 66) and the remaining 116,667 dry tons are processed by the plant in that month.

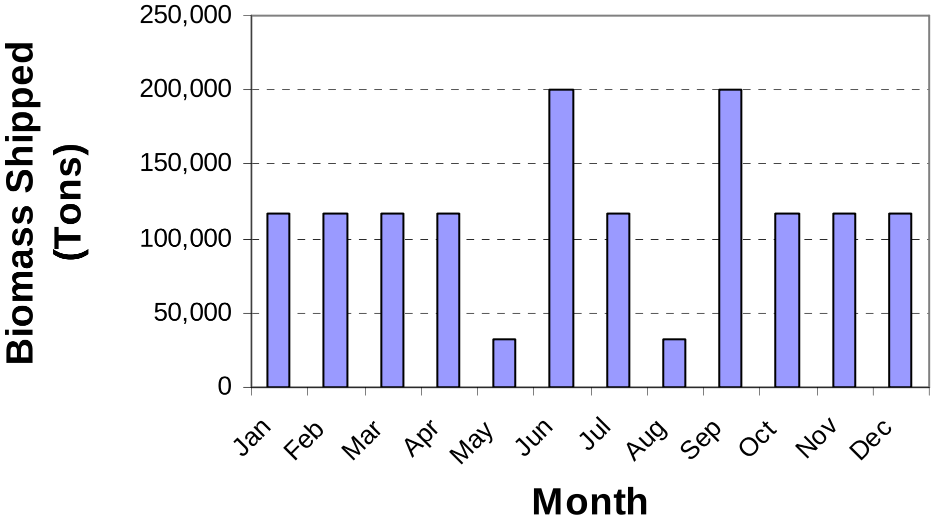


**Figure 67. Total dry tons of biomass feedstock shipments from the supplying counties to the biorefinery in each month for the RES 100-60 scenario of the crop residue model**

In the month of July 541,436 dry tons of biomass are harvested (Figure 64). Of this amount 116,751 are shipped to the biorefinery (Figure 67) leaving the remainder i.e. 541,436 dry tons – 116,751 dry tons = 424,686 dry tons in field storage. Since there were 223,878 dry tons put in the field storage by the end of the month of June, accounting for 0.5% storage losses incurred during the month of July this becomes 223,878 dry tons × 0.995 = 222,759 dry tons at the end of July. Adding this amount to 424,686 put in storage in July, total biomass in field storage at the end of July becomes 424,686 + 222,759 = 647,445 dry tons (Figure 65). Of the 116,751 dry tons shipped to the biorefinery in the month of July 84,000 dry tons are put in on-site storage to reach maximum capacity. This leaves 116,751 – 84,000 = 32,751 dry tons, which are added to the 84,000 dry tons of biomass that were left in on-site storage at the end of the month of June less storage losses. Considering storage losses at the biorefinery, these 84,000 dry tons become 84,000 dry tons × 0.999 = 83,916. Adding this to the 32,751 dry tons shipped we get 83,916 dry tons + 32,751 dry tons = 116,667 dry tons processed in the month of July. Since no harvesting of biomass is done in the month of August, shipment is made of 32,751 from the in-field storage to the biorefinery (Figure 67). At the biorefinery, the 84,000 dry tons that were put in storage in July (Figure 66), after accounting for storage losses, are added to the shipped 32,751 dry tons of biomass to get 116,667 dry tons processed in the month of August. By processing the 84,000 dry tons that were stored in July without replenishing the on-site storage, it leaves zero inventories in on-site storage for the month of August. Replenishment of both in-field and on-site storage reserves resume in the month of September when harvesting of corn stover begins (Figure 64 through Figure 67).

## Comparison between Model RES 100-60 and Sensitivity Model RES 100-40

Figure 68 through Figure 75 show charts of some of the results of RES 100-40 compared to RES 100-60 scenario. Figures 68 through 70 show that significantly more land is harvested by RES 100-40 compared to RES 100-60. However, the quantity of biomass harvested by RES 100-40 is slightly higher than that of RES 100-60 (Figures 71 and 72). RES 100-40 stores slightly higher quantities of biomass feedstock than RES 100-60 (Figure 73). This results in a very slight increase in the field storage cost (Table 15). Figure 74 shows that RES 100-40 stores biomass in the month of August on-site while RES 100-60 does not have any biomass in on-site storage in that month. Figure 75 is a chart of biomass shipments to the biorefinery, which shows no any significant differences.

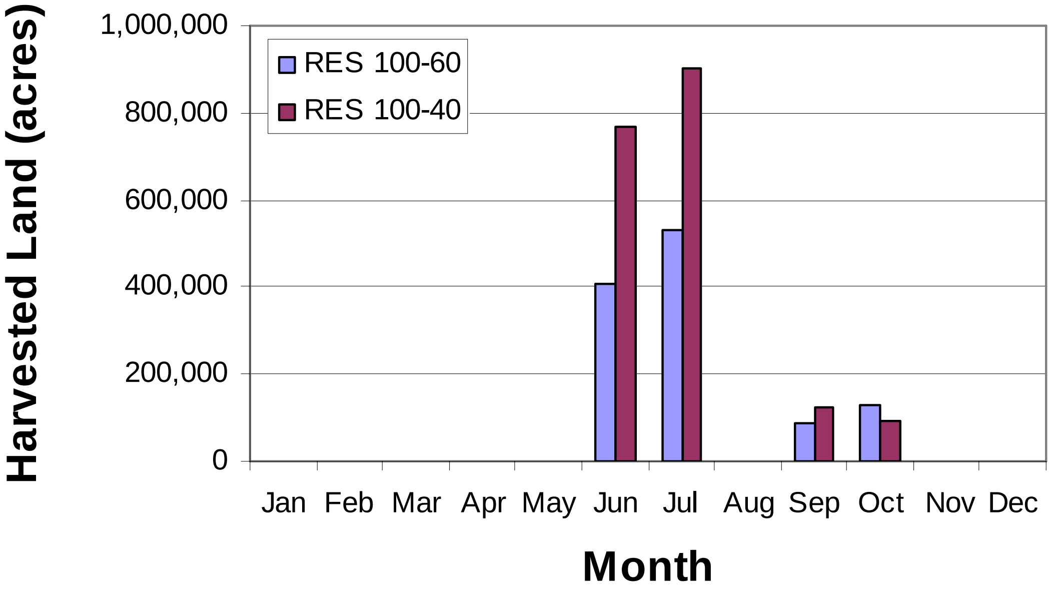


**Figure 68. Total number of acres harvested from all crop residues supplying counties by month for RES 100-60 and RES 100-40 models**

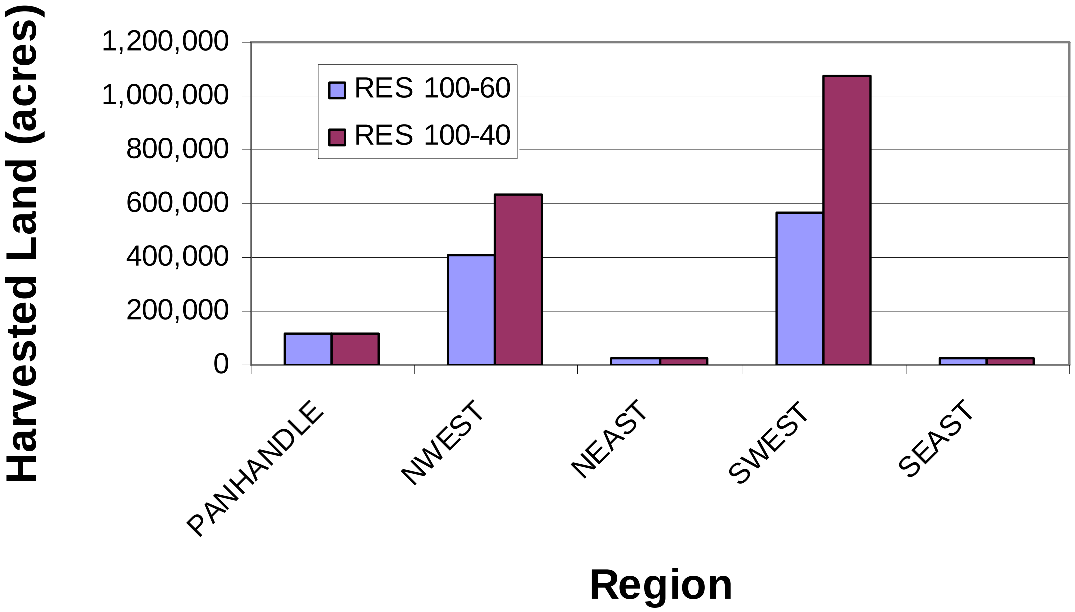


**Figure 69. Total number of acres harvested from all crop residues supplying counties by region for RES 100-60 and RES 100-40 models**

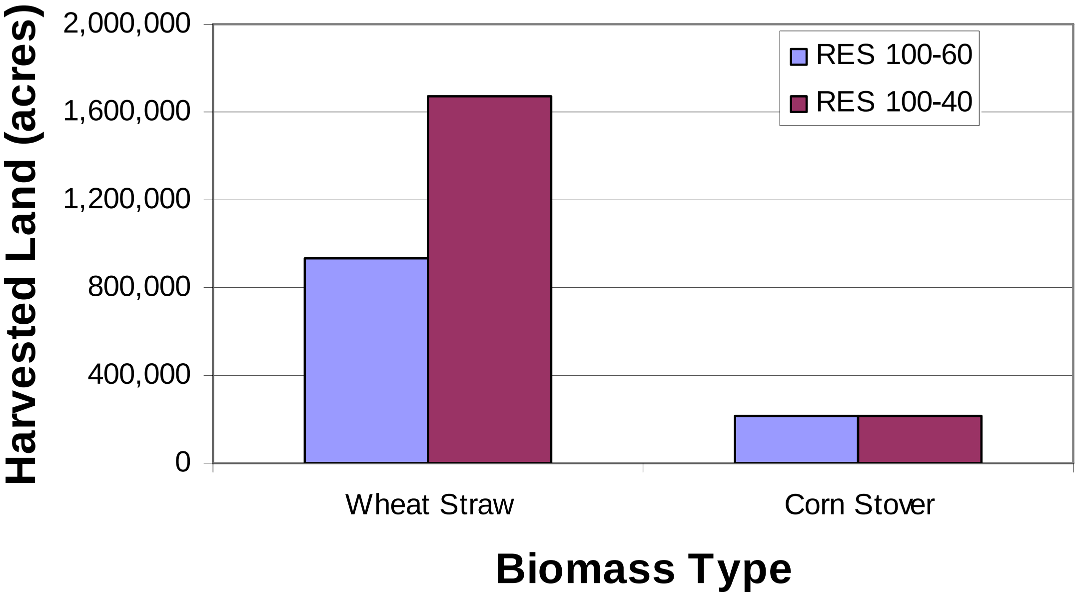


**Figure 70.** **Total number of acres harvested from all supplying counties by biomass feedstock type for RES 100-60 and RES 100-40 models**

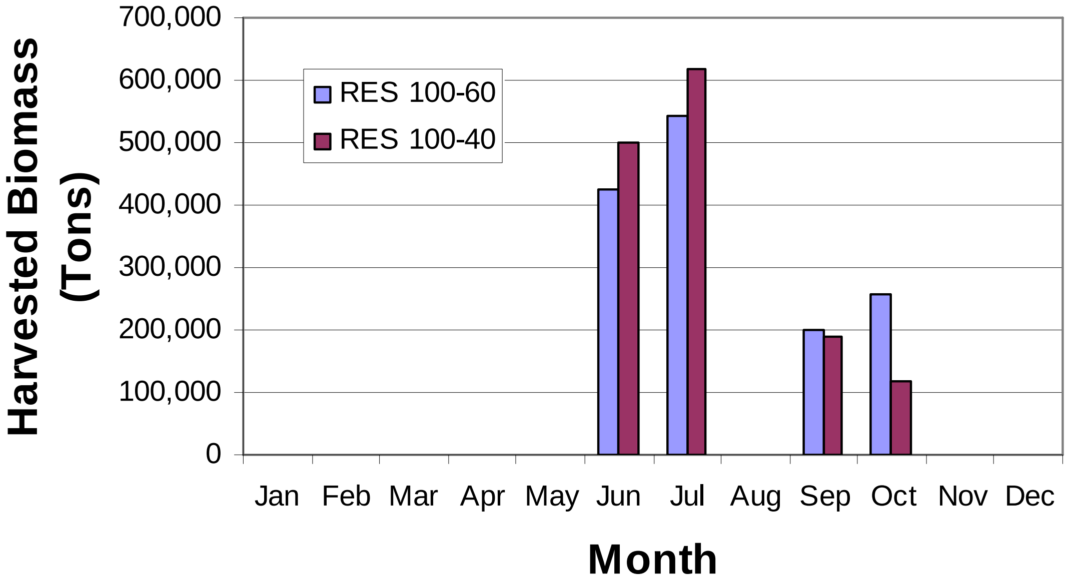


**Figure 71.** **Total dry tons of biomass harvested from all supplying counties by month for RES 100-60 and RES 100-40 models**

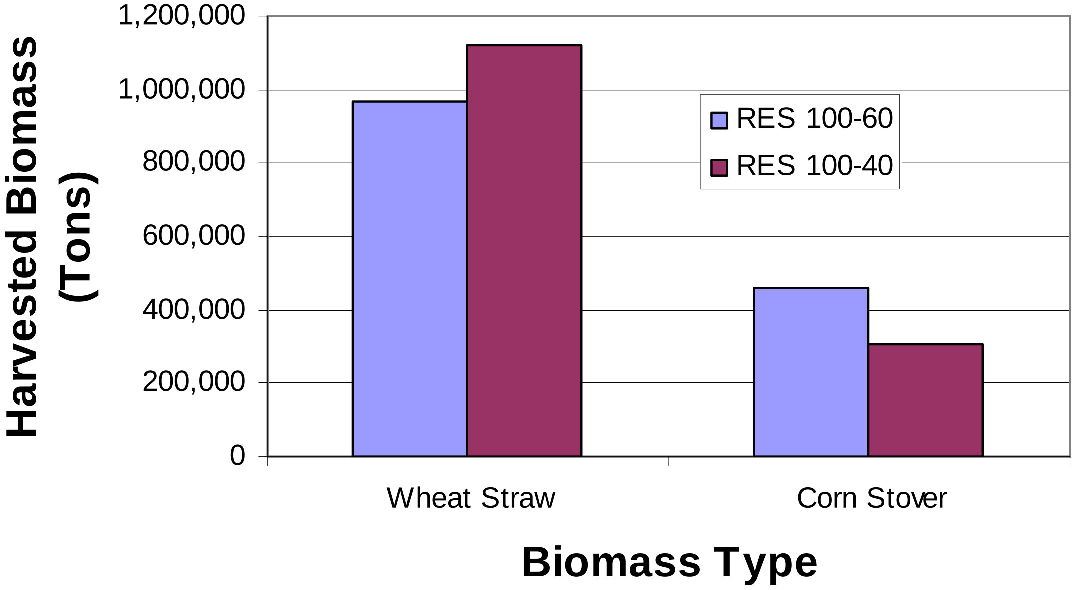


**Figure 72.** **Total tons of biomass harvested from all supplying counties by biomass feedstock type for RES 100-60 and RES 100-40 models**

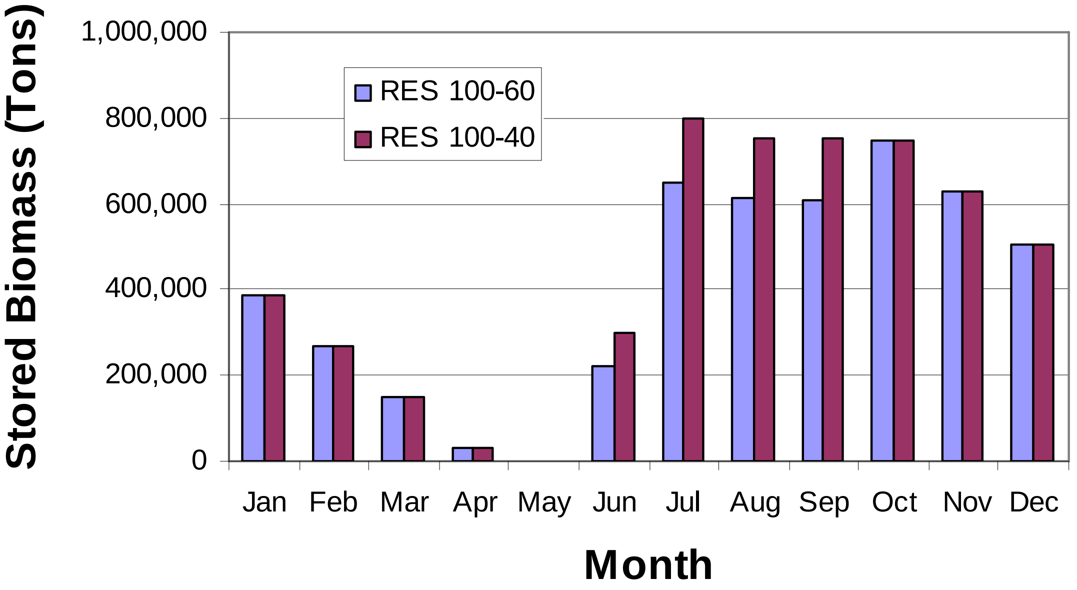


**Figure 73.** **Total dry tons of stored biomass feedstock from all in-field storage facilities in each month for RES 100-60 and RES 100-40 models**

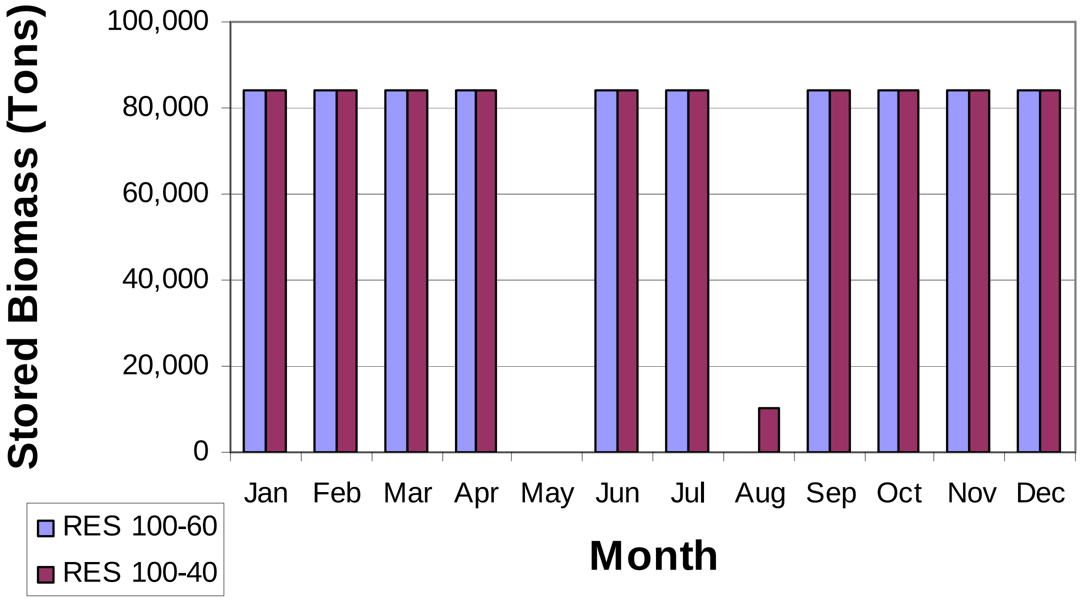


**Figure 74.** Total dry tons of stored biomass feedstock at on-site storage facilities in each month for RES 100-60 and RES 100-40 models

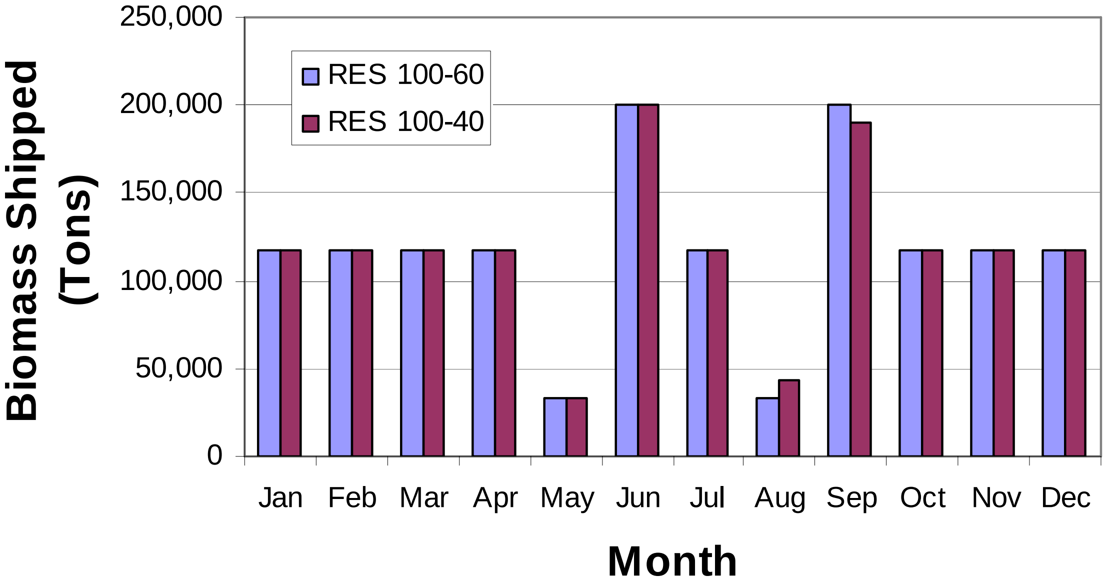


**Figure 75.** Total dry tons of biomass feedstock shipments from the supplying counties to the biorefinery in each month for RES 100-60 and RES 100-40 models

## Comparison between Model RES 100-60 and Sensitivity Model RES 50-60

Figure 76 through Figure 83 show charts of some of the results of RES 50-60. The graphs show the same trend as in RES 100-60. Figure 76 through Figure 80 show that slightly more acres and tons of biomass are harvested in RES 50-60 than in RES 100-60 scenario. As in RES 100-40, most of the extra harvested acres and tons are wheat straw in the Northwest region. Figure 81 show that RES 50-60 stores more biomass than RES 100-60. This results in a slight increase in the in-field storage cost in RES 50-60 (Table 15). RES 50-60 uses the on-site storage at maximum in the month of August while RES 100-60 stores nothing (Figure 82). This is because RES 50-60 transports more than three times as much biomass in the month of August to the biorefinery than RES 100-60 scenario (Figure 83).

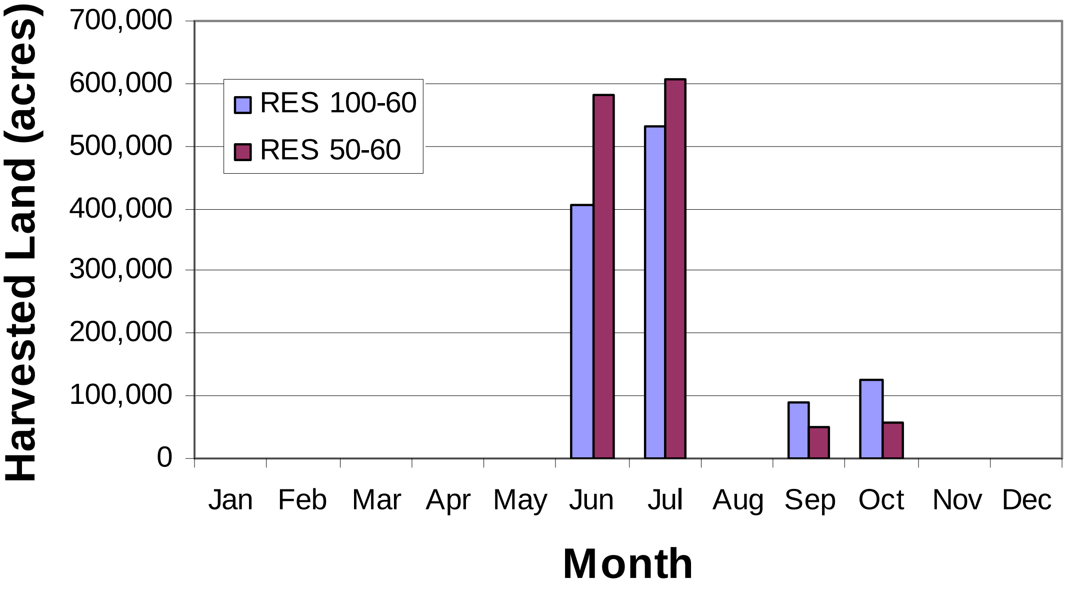


**Figure 76. Total number of acres harvested from all crop residues supplying counties by month for RES 100-60 and RES 50-60 models**

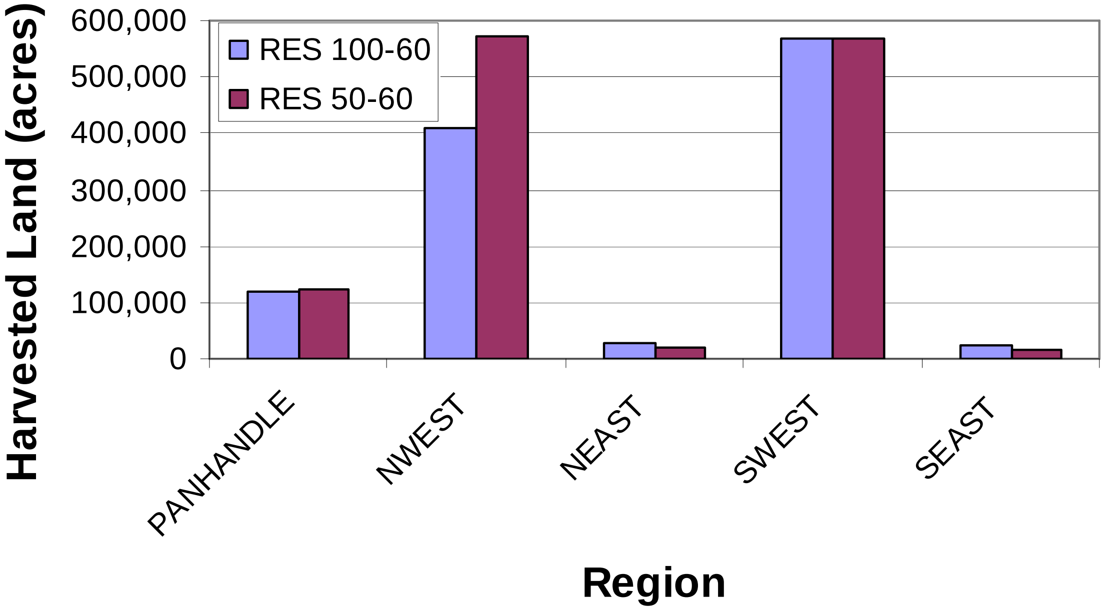


**Figure 77.** **Total number of acres harvested from all supplying counties in each region for RES 100-60 and RES 50-60 models**

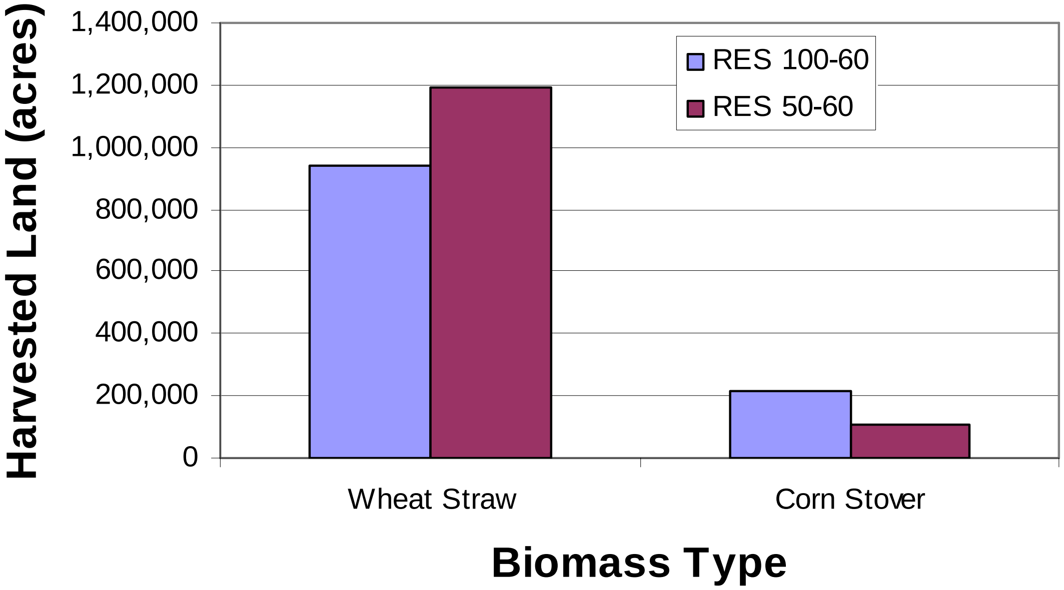


**Figure 78.** **Total number of acres harvested from all supplying counties by biomass feedstock type for RES 100-60 and RES 50-60 models**

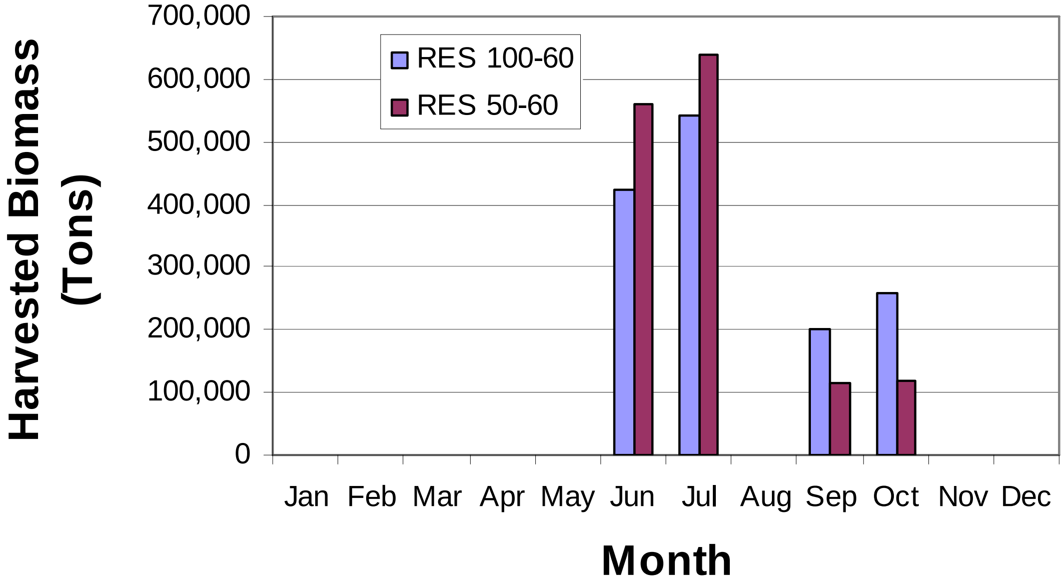


**Figure 79.** **Total dry tons of biomass harvested from all supplying counties by month for RES 100-60 and RES 50-60 models**

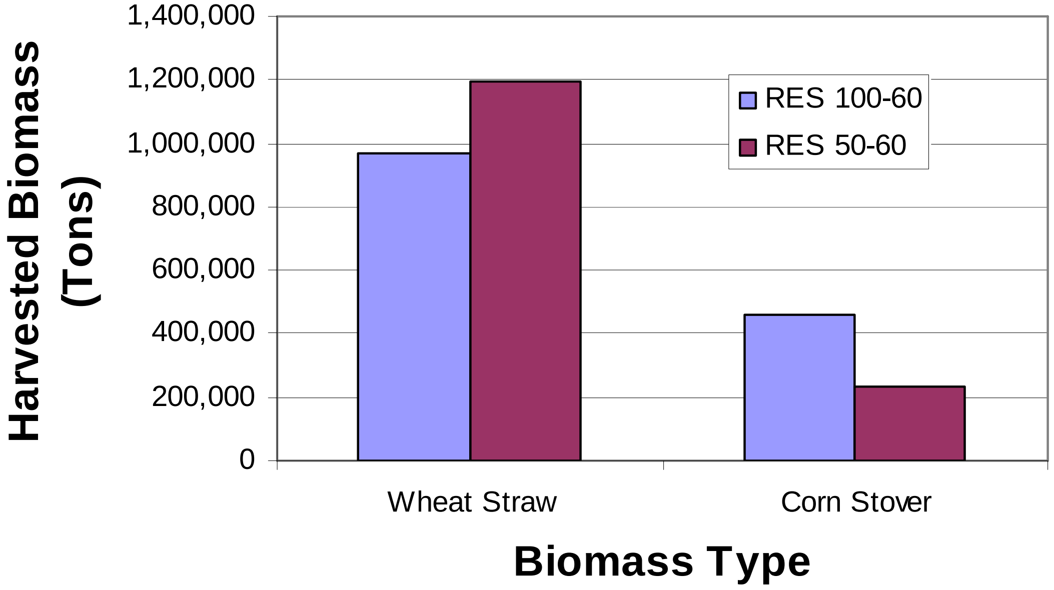


**Figure 80.** **Total tons of biomass harvested from all supplying counties by biomass feedstock type for RES 100-60 and RES 50-60 models**

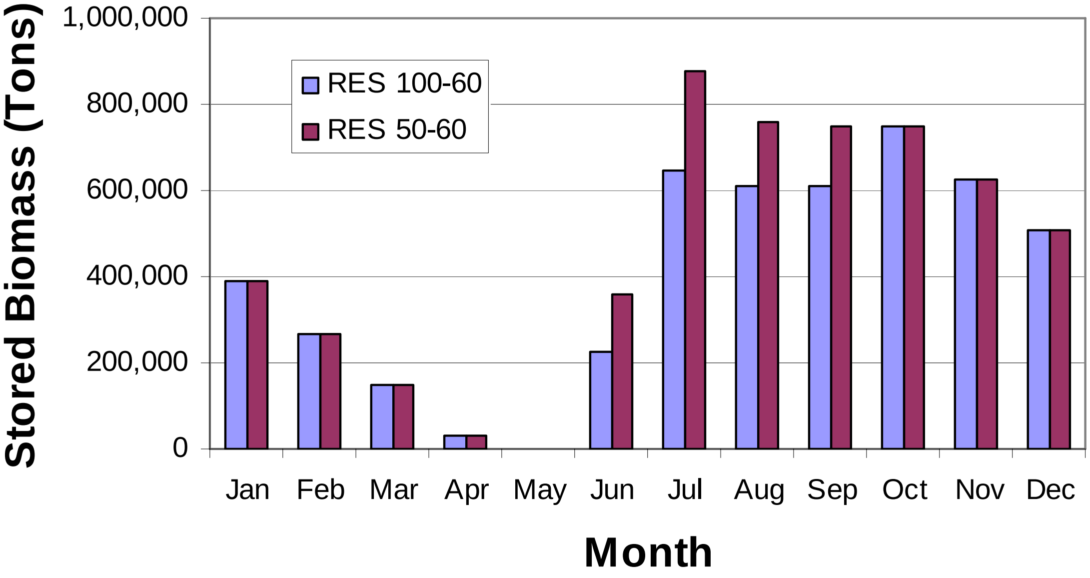


**Figure 81.** **Total dry tons of stored biomass feedstock from all in-field storage facilities in each month for RES 100-60 and RES 50-60 models**

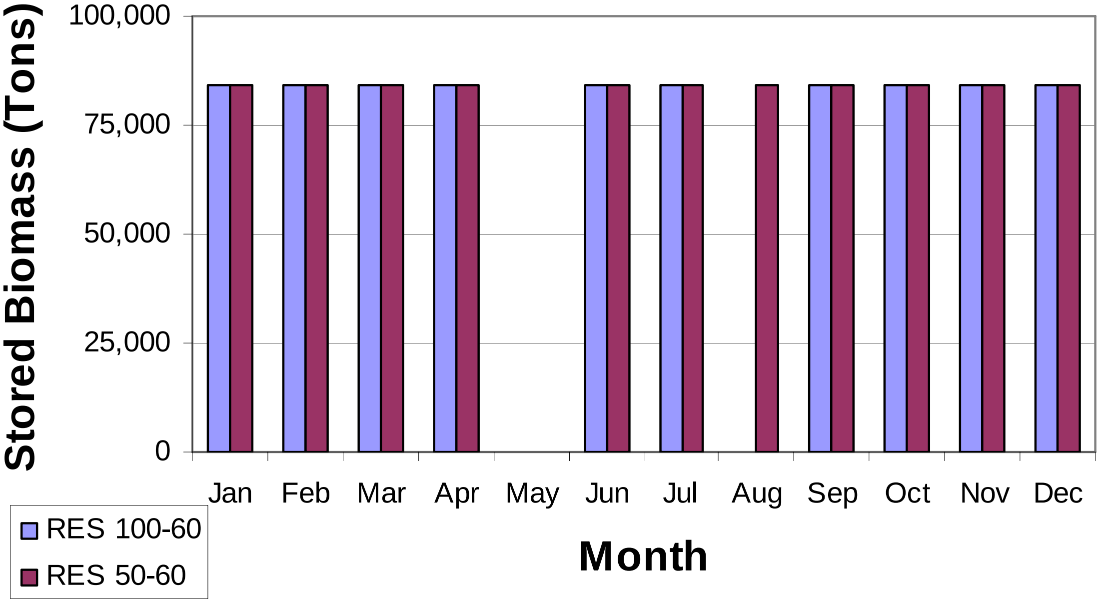


**Figure 82.** **Total dry tons of stored biomass feedstock at on-site storage facilities in each month for RES 100-60 and RES 50-60 models**

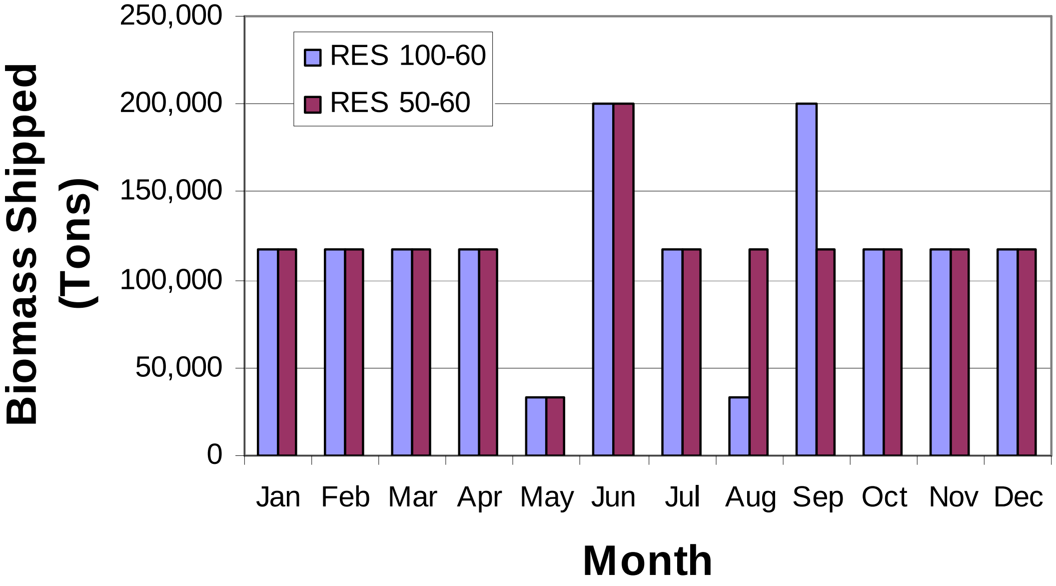


**Figure 83. Total dry tons of biomass feedstock shipments from the supplying counties to the biorefinery in each month for RES 100-60 and RES 50-60 models**

The higher shipments and storage in the month of August are as a result of more feedstock harvested by RES 50-60 in the months of June and July compared to RES 100-60 (Figure 79).

## Comparison between Model RES 100-60 and Sensitivity Model RES 25-60

Figure 84 through Figure 91 give some of the results for RES 25-60. Since RES 25-60 selects a medium plant compared to the large plant selected by RES 100-60 scenario no comparisons are made across scenarios.

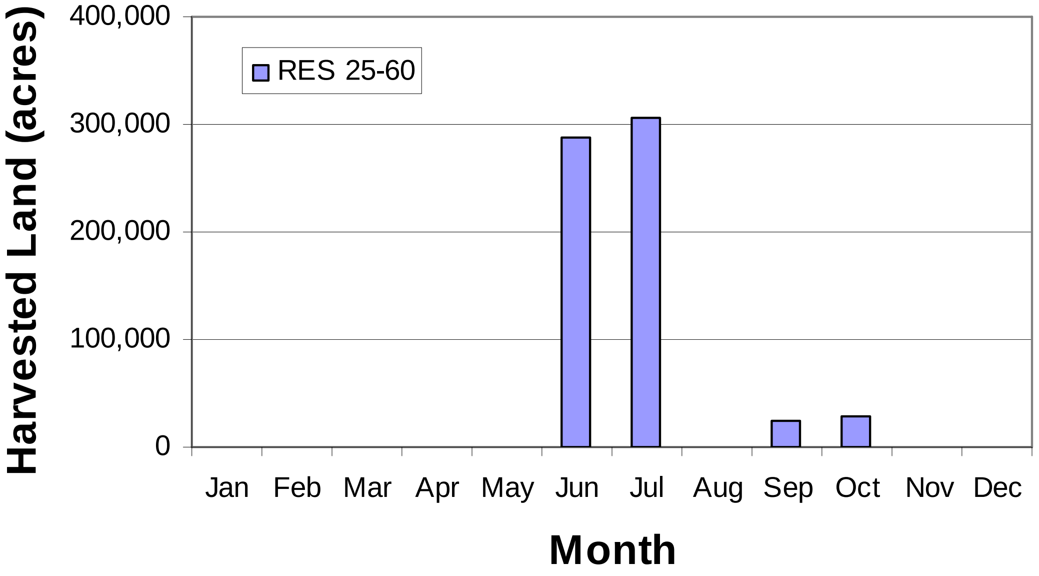


**Figure 84. Total number of acres harvested from all crop residues supplying counties by month for RES 25-60**

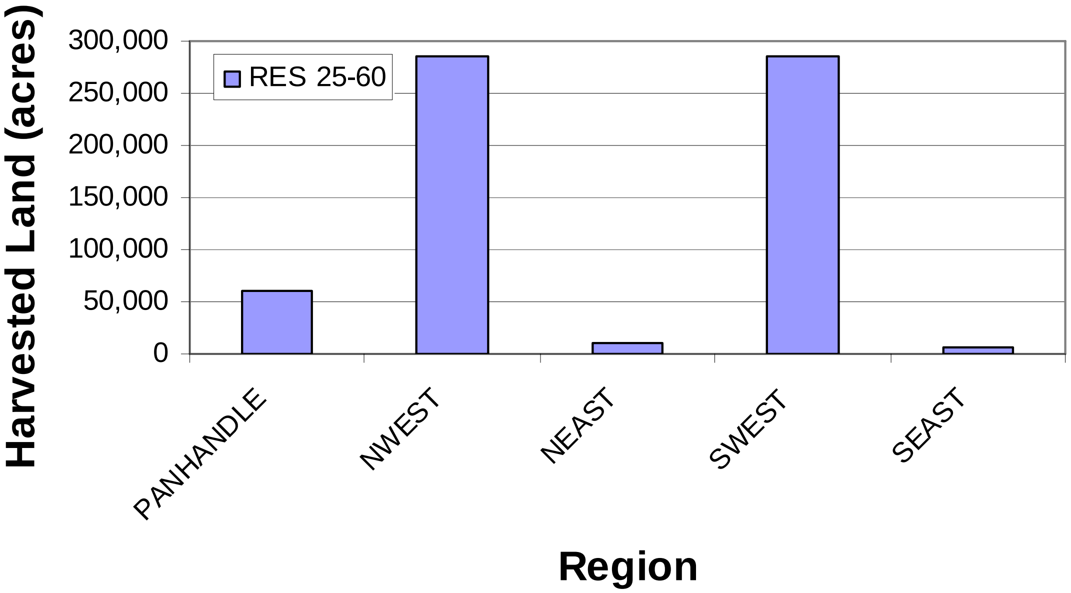


**Figure 85. Total number of acres harvested from all supplying counties in each region for RES 25-60**

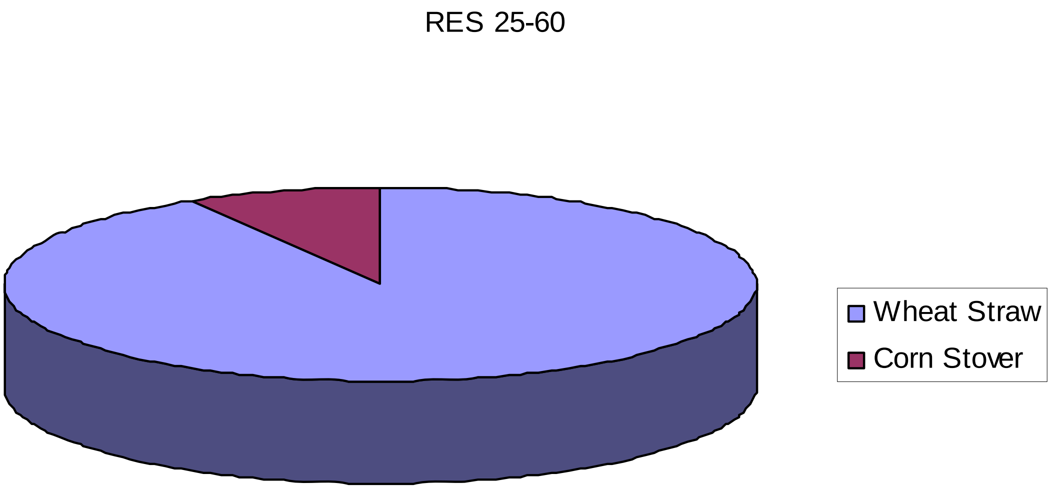


**Figure 86.** **Total number of acres harvested from all supplying counties by biomass feedstock type for RES 25-60**

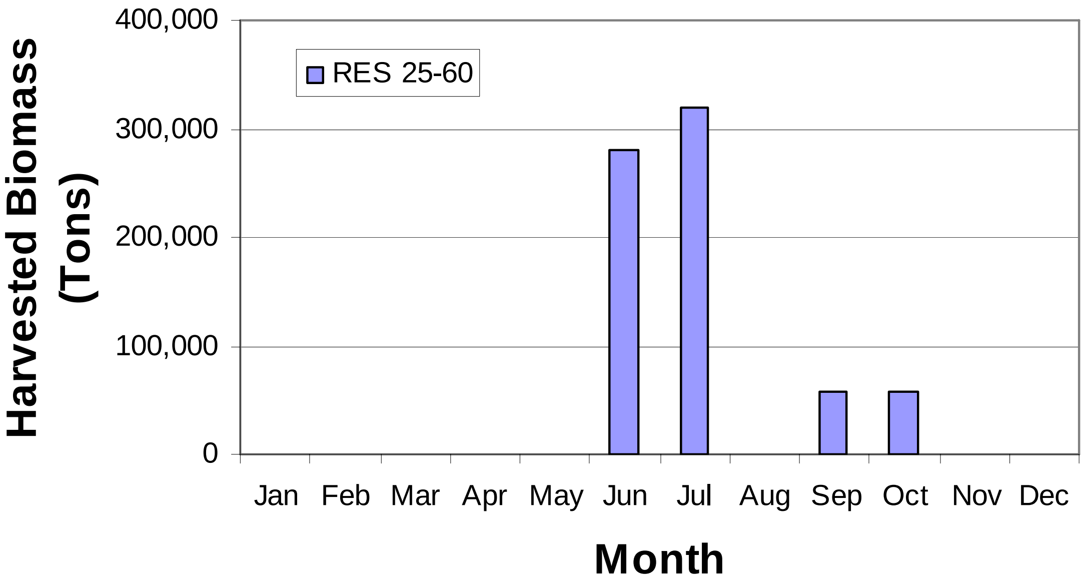


**Figure 87.** **Total dry tons of biomass harvested from all supplying counties by month for RES 25-60**

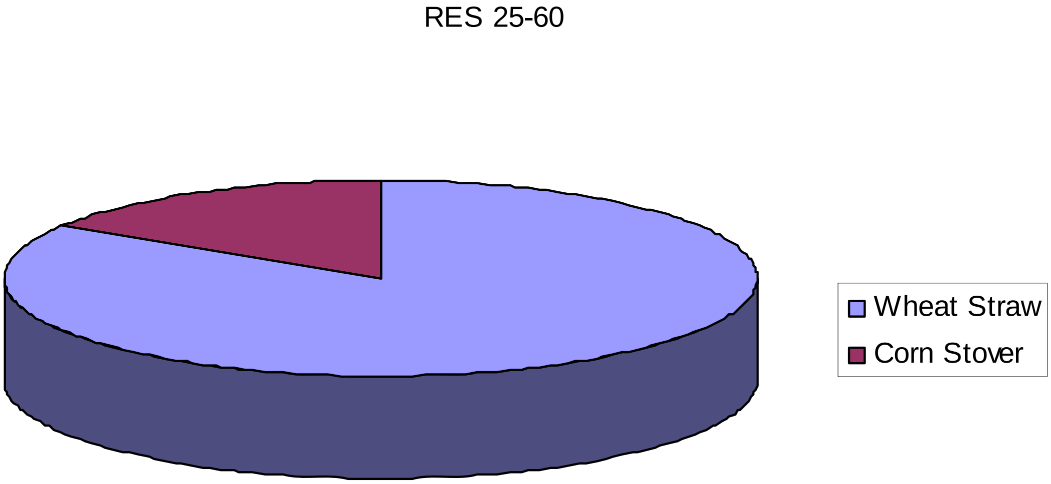


**Figure 88. Total tons of biomass harvested from all supplying counties by biomass feedstock type for RES 25-60**

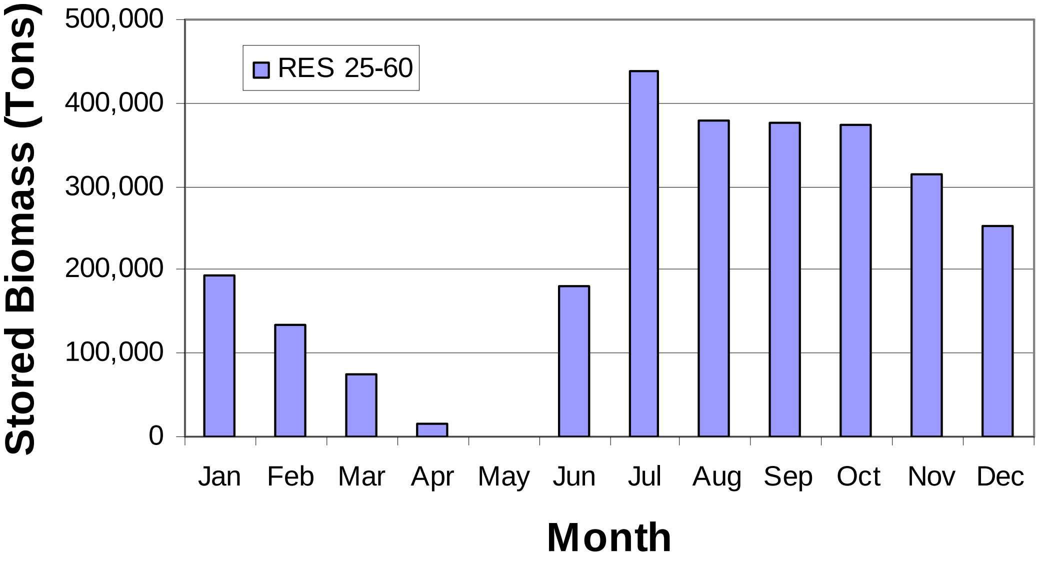


**Figure 89. Total dry tons of stored biomass feedstock from all in-field storage facilities in each month for RES 25-60**

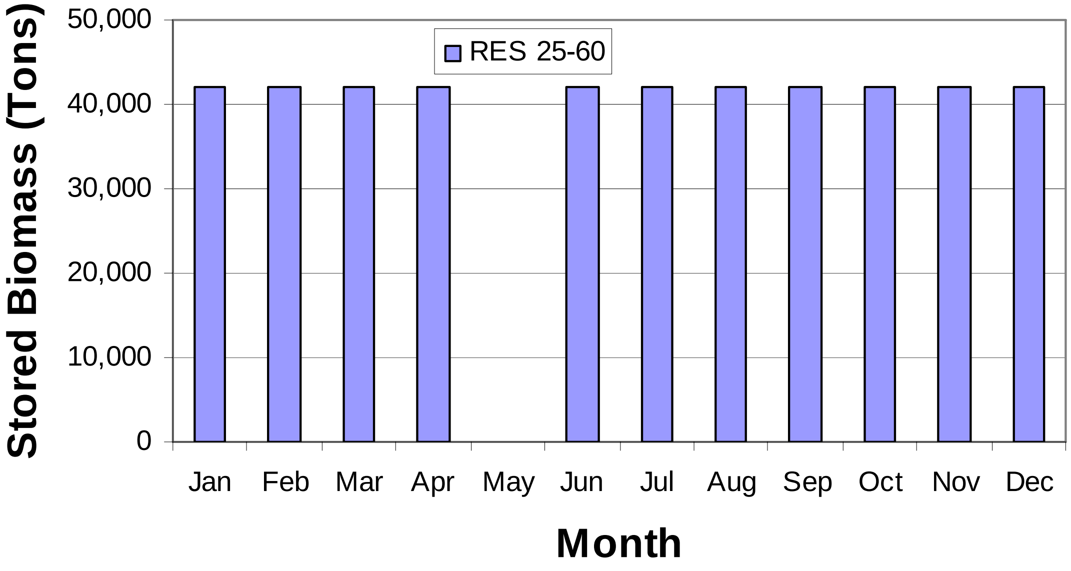


**Figure 90. Total dry tons of stored biomass feedstock at on-site storage facilities in each month for RES 25-60**

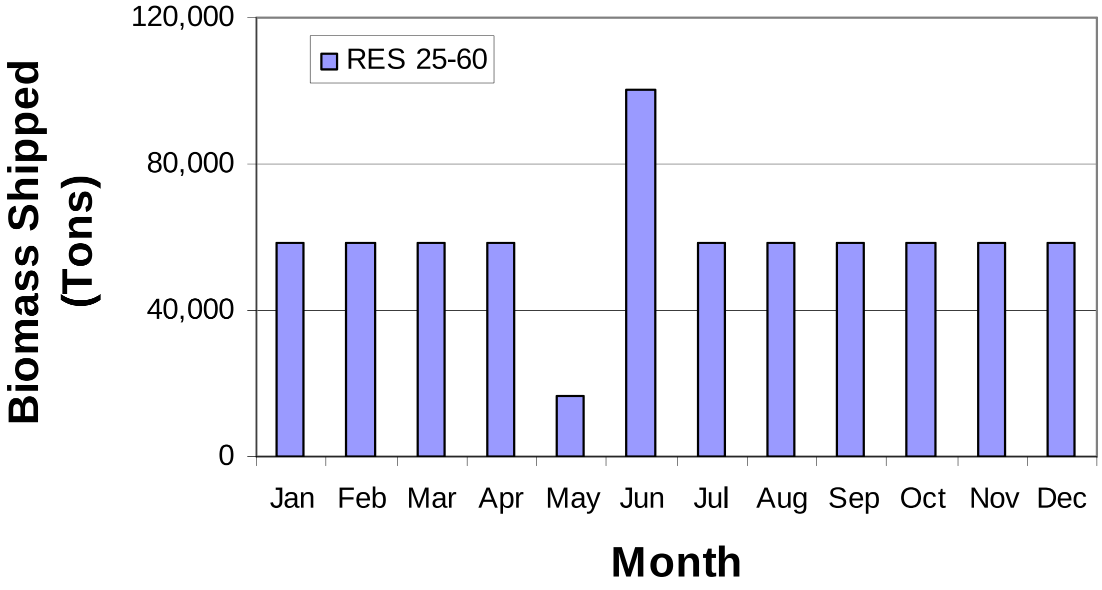


**Figure 91. Total dry tons of biomass feedstock shipments from the supplying counties to the biorefinery in each month for RES 25-60**

## Biorefinery Feedstock Production on Conservation Reserve Program Land

### Comparison between Restricted and Unrestricted Harvest Season

The third objective was to determine the cost to deliver a ton of LCB from CRP land to biorefineries, optimally located in Oklahoma, that have capacity to process either 1,000 or 2,000, or 4,000 dry tons per day. To achieve this objective, a GAMS model was developed to solve and analyze the restricted harvest season model and sensitivity analyses. A total of six scenarios were analyzed. These scenarios were differentiated by biorefinery feedstock requirements (either 1,000 or 2,000 or 4,000 tons of biomass per day) to determine the tradeoff between feedstock transportation cost and biorefinery size. The scenarios were also differentiated by the length of the harvest season (either the restricted harvest season or the unrestricted harvest season) to determine the potential economic consequences of a policy restricted harvest season. The three models that assume unrestricted harvest season were treated as the sensitivity analyses. In both the restricted and unrestricted harvest season model, one of the three models was restricted to select a small plant size, another was restricted to select a medium plant size and the third model was restricted to select a large biorefinery plant size. The results for the models are presented in this section.

Table 16 includes a summary of results from the six scenarios. As the size of the biorefinery increases from 1,000 to 4,000 tons per day, the average one-way distance to transport biomass from the field to the biorefinery increases from 83 miles to 147 miles for the restricted-harvest season. This increases the transportation cost from $11.71 to $19.34 per ton. The increase in biorefinery size from 1,000 to 4,000 tons per day requires

**Table 16. Results of Models Solved to Determine the Cost to Delivery a Steady Flow of Biomass from Conservation Reserve Program Acres in Kansas, Oklahoma and Texas to 1,000, 2,000 and 3,000 Tons Per Day Biorefineries for Both a Restricted Harvest Season and an Unrestricted Harvest Season**

| Item | Restricted Harvest | | | Unrestricted Harvest | | |
|---|---|---|---|---|---|---|
| | Biorefinery Size (tons/day) | | | | | |
| | 1,000 | 2,000 | 4,000 | 1,000 | 2,000 | 4,000 |
| Land Rent Cost ($/ton) | 7.90 | 7.68 | 6.99 | 7.76 | 7.53 | 7.38 |
| Harvest Cost ($/ton) | 23.15 | 23.14 | 30.10 | 9.87 | 10.69 | 10.69 |
| Field Storage Cost ($/ton) | 1.39 | 1.39 | 1.39 | 0.56 | 0.56 | 0.56 |
| Transportation Cost ($/ton) | 11.71 | 17.04 | 19.34 | 9.40 | 12.41 | 17.71 |
| Total Cost of Delivered Feedstock ($/ton) | 44.16 | 49.26 | 57.83 | 27.58 | 31.19 | 36.34 |
| Harvested Acres | 282,209 | 548,755 | 998,906 | 273,467 | 531,011 | 1,040,307 |
| Harvest Units (Number)[a] | 20 | 40 | 104 | 6 | 13 | 26 |
| Average Investment in Harvest Machines ($,000) | 11,800 | 23,600 | 61,360 | 3,540 | 7,670 | 15,340 |
| Harvest Months (Number)[b] | 3 | 3 | 3 | 8 | 8 | 8 |
| Total Biomass Harvested (tons)[c] | 357,051 | 714,425 | 1,428,074 | 352,507 | 705,431 | 1,410,380 |
| Average Distance Hauled (miles) | 83 | 128 | 147 | 63 | 89 | 134 |

[a] A harvest unit includes ten laborers, three mowers, three rakes, three balers, nine tractors, and one transport stacker.

[b] In Kansas, Oklahoma, and Texas harvest of CRP land is currently restricted. In the absence of policy restrictions, for the region of the study, biomass could be harvested on CRP grasslands from July through February.

[c] The biorefinery is expected to operate 350 days per year. The model accounts for storage losses. Total storage losses are greater when harvest is restricted.

harvest of more acres, transportation from greater distances, and increases the cost to deliver a flow of feedstock from $44 to $58 per ton. The results are similar for the case of an unrestricted harvest season. Average transportation distance increases from 63 to 134 miles, and, transportation cost increases from $9.40 to $17.71 per ton as biorefinery size increases from 1,000 to 4,000 tons per day. Considering the large plant in the restricted harvest season the total cost to deliver a ton of biomass to a biorefinery is $22.46 per ton more than that in the base model when multiple biomass feedstock are harvested for an unrestricted harvest season. The average feedstock transport distance for both the restricted harvest and unrestricted harvest window for all three biorefinery sizes is graphed in Figure 92. As described in Table 16 and shown in Figure 93, restricting the harvest window increases the cost to deliver a ton of biomass by $17 to$22 per ton depending upon biorefinery capacity. The harvest window restriction increases harvest, storage and transportation costs per ton of biomass.

A coordinated set of harvest machines was defined as a harvest unit and included in the model as an integer investment activity. As the size of the biorefinery increases from 1,000 to 4,000 tons per day, the required number of harvest units increases from 20 to 104, for the restricted harvest season, and from 6 to 26 harvest units for the unrestricted harvest season (Table 16 and Figure 94). For a 4,000-tons per day biorefinery, if the harvest window is restricted, the model selects 104 harvest units as optimal (Table 16). Since a harvest unit includes three mowers, three rakes, three balers, nine tractors, and one transport stacker, the 4,000 tons per day biorefinery with a restricted harvest window would require 936 tractors, 312 mowers, rakes, and balers, and 104 transport stackers. The estimated average investment in these harvest machines is

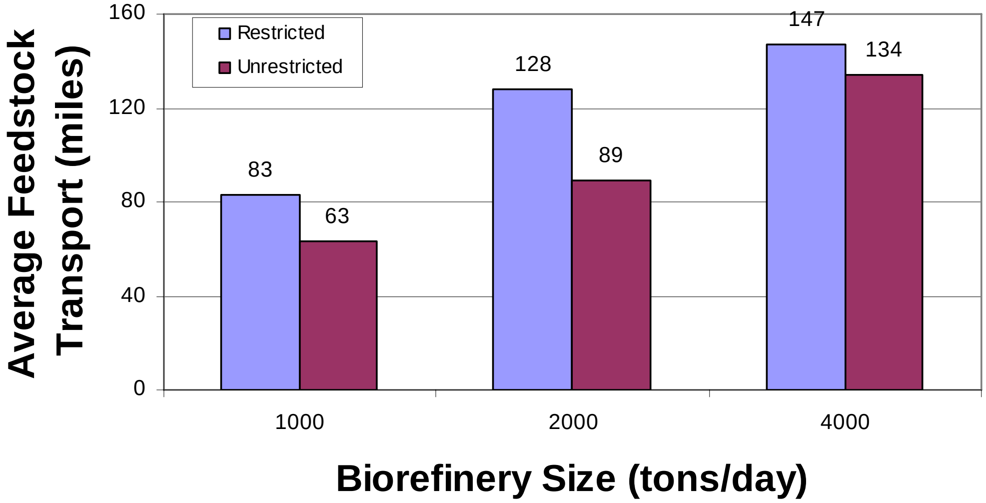


**Figure 92.** **Estimated average one-way distance to transport biomass to a biorefinery from feedstock produced on CRP grasslands in Kansas, Oklahoma and Texas from both a restricted harvest season and an unrestricted harvest season for three biorefinery sizes**

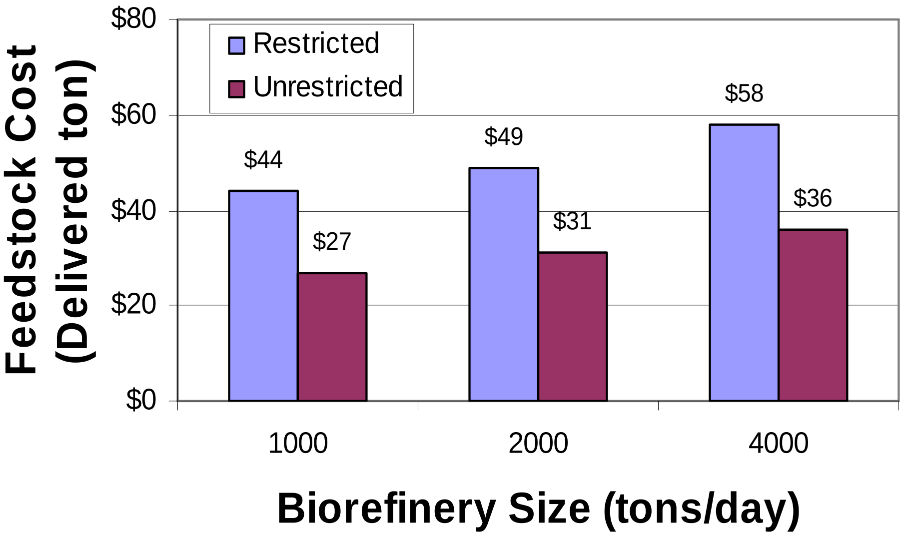


**Figure 93.** **Estimated cost to deliver a ton of biomass to a biorefinery from feedstock produced on CRP grasslands in Oklahoma, Kansas, and Texas from both a restricted harvest season and an unrestricted harvest season for three biorefinery sizes**

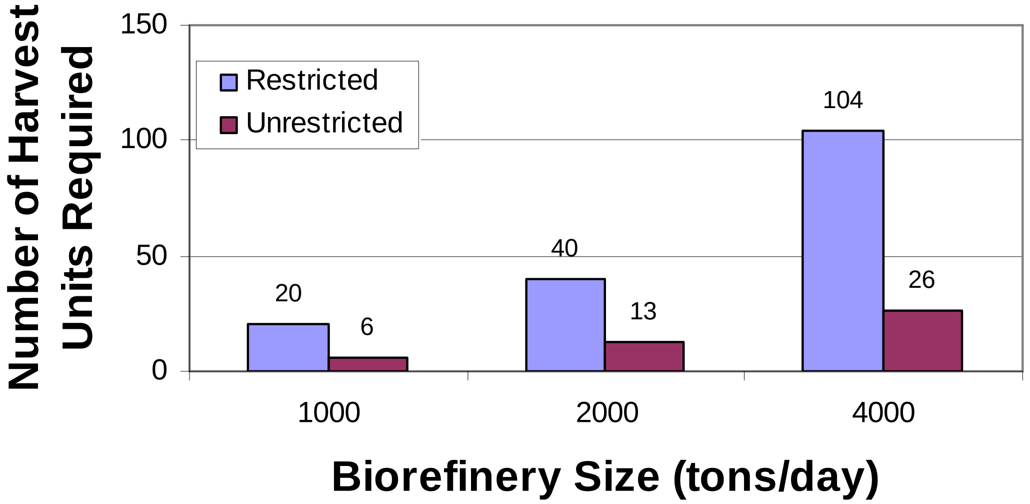


**Figure 94. Estimated number of harvest units with capacity to harvest a given quantity of biomass produced on CRP grasslands in Kansas, Oklahoma and Texas from both a restricted harvest season and an unrestricted harvest season for three biorefinery sizes**

approximately $61 million (Table 16). If the policy imposed harvest season restriction was lifted, and harvesting was permitted from July through February, the number of harvest units required to harvest biomass for a 4,000 tons per day biorefinery could be reduced from 104 to 26 (Figure 94). And, the average investment in harvest machines could be reduced from $61 million to $15 million (Table 16).

## Comparison of Land Harvested between Restricted and Unrestricted Models

Figures 95 through 97 give the acres harvested by month for a 1,000, 2,000 and 4,000 tons per day biorefineries, respectively, for both a restricted and an unrestricted harvest season. Figure 95 shows that, with an unrestricted harvest season, harvested acres would increase steadily from July through December declining in the months of January and February. When the harvest season is restricted then harvesting of acres of land would concentrate in the months August and September, later in the harvest season.

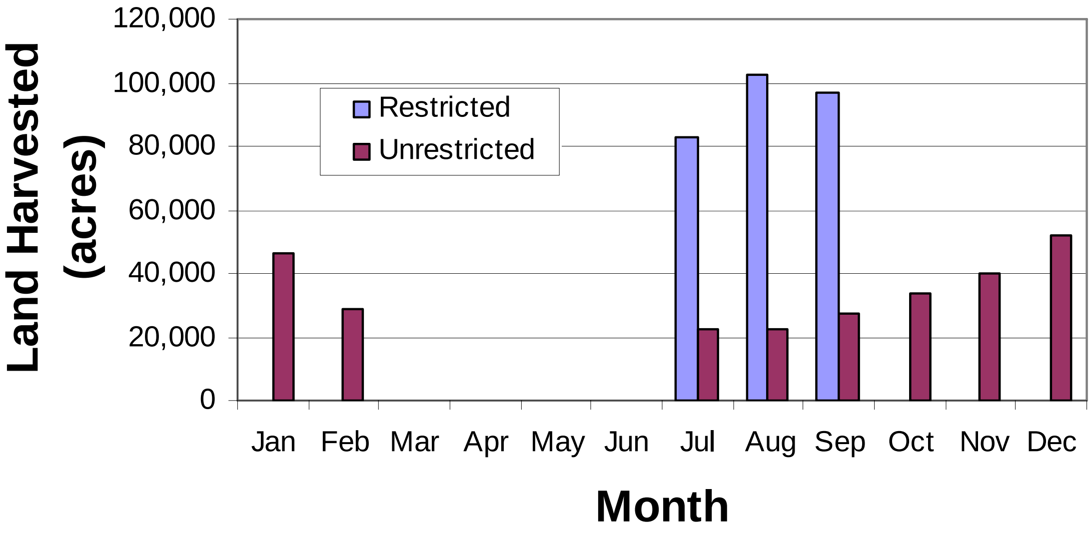


**Figure 95. Estimated acres of land harvested per month for a 1,000 tons per day biorefinery from feedstock produced on CRP grasslands in Kansas, Oklahoma and Texas from both a restricted harvest season and an unrestricted harvest season**

Figure 96 shows that, with an unrestricted harvest season, the number of acres harvested would be more or less the same with slight increases in the months of October and November. A similar trend is shown in Figure 97. But Figure 96 shows that when the harvested season is restricted the model harvests more or less the same amount each of the three months. On the other hand Figure 97 shows that with a restricted harvest season most of the land would be harvested in the last month of the harvest season, thus the month of September.

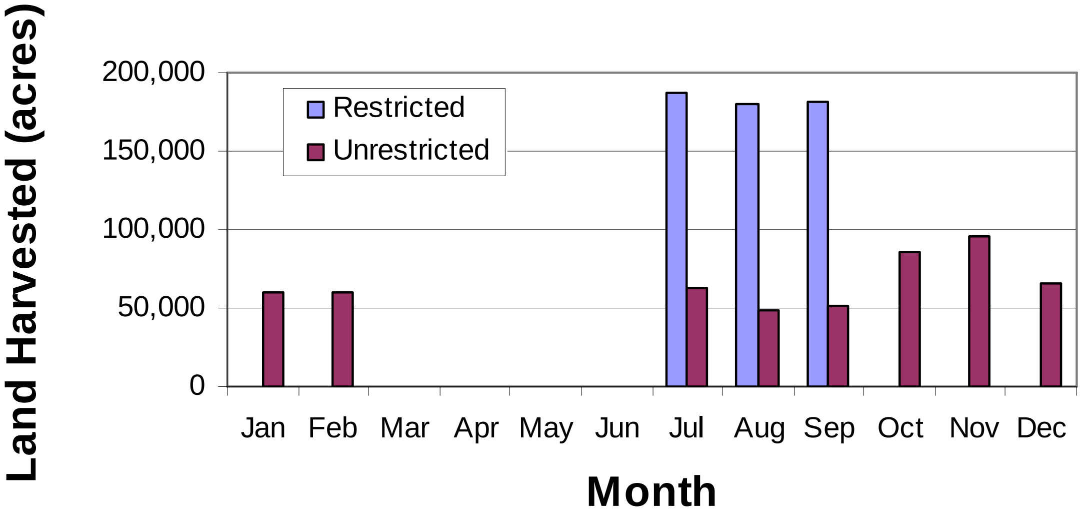


**Figure 96.** Estimated acres of land harvested per month for a 2,000 tons per day biorefinery from feedstock produced on CRP grasslands in Kansas, Oklahoma and Texas from both a restricted harvest season and an unrestricted harvest season

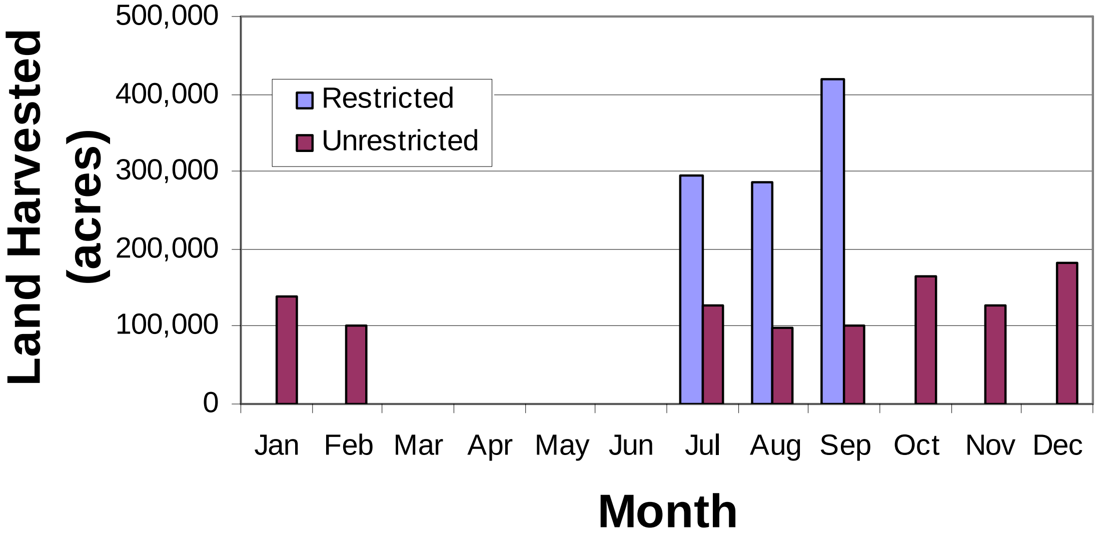


**Figure 97.** Estimated acres of land harvested per month for a 4,000 tons per day biorefinery from feedstock produced on CRP grasslands in Kansas, Oklahoma and Texas from both a restricted harvest season and an unrestricted harvest season

Figures 98 through 100 show that for the restricted harvest season most of the land harvested is in the Oklahoma Panhandle and the Texas Panhandle both of which have dominant acres in old world bluestem. This is true with all biorefinery sizes except for the model with the large plant which harvested more acres in southern Kansas than in Oklahoma Panhandle. The Figures show that when the harvest season is unrestricted most of the harvested acres are in southern Kansas, which is a region dominant in mixed native prairies. Similarly, this was true with the exception of the model with the large plant which harvested almost the same number of acres in southern Kansas as in the Texas Panhandle.

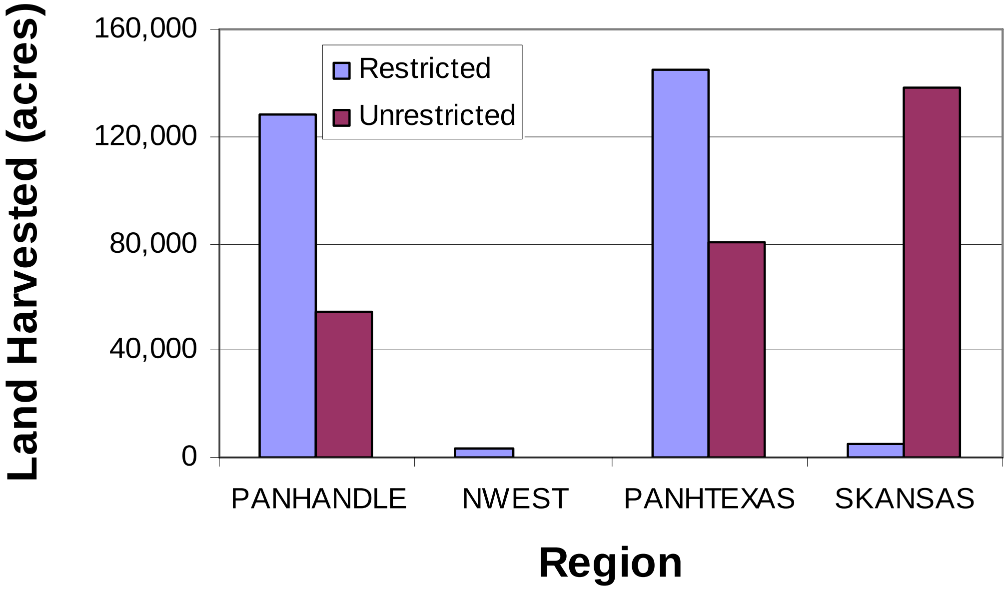


**Figure 98. Estimated acres of land harvested by region for a 1,000 tons per day biorefinery from feedstock produced on CRP grasslands in Kansas, Oklahoma and Texas from both a restricted harvest season and an unrestricted harvest season**

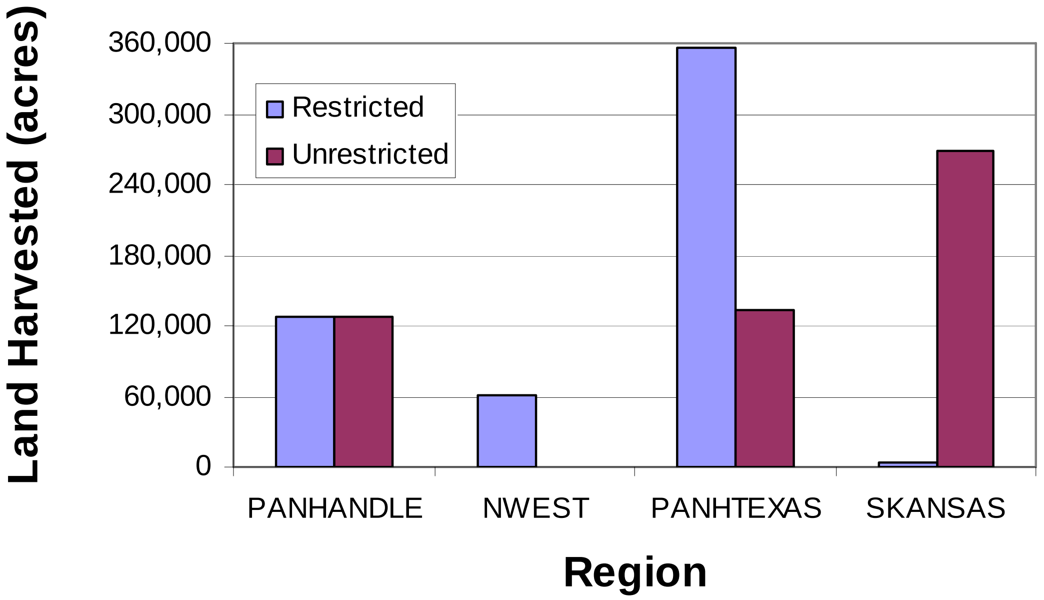


**Figure 99.** **Estimated acres of land harvested by region for a 2,000 tons per day biorefinery from feedstock produced on CRP grasslands in Kansas, Oklahoma and Texas from both a restricted harvest season and an unrestricted harvest season**

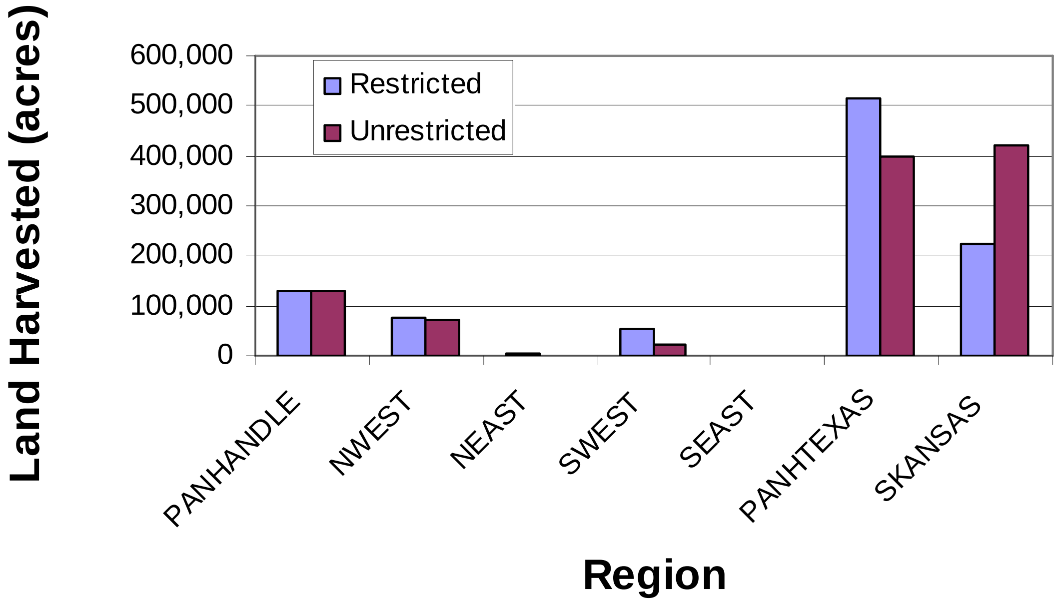


**Figure 100.** **Estimated acres of land harvested by region for a 4,000 tons per day biorefinery from feedstock produced on CRP grasslands in Kansas, Oklahoma and Texas from both a restricted harvest season and an unrestricted harvest season**

## Comparison of LCB Harvested between Restricted and Unrestricted Models

Figures 101 through 103 include charts of the estimated quantity of feedstock harvested per month for a 1,000, 2,000 and 4,000 tons per day biorefineries, respectively, for both a restricted and an unrestricted harvest season. Monthly harvest is restricted by both the number of expected harvest days and by the endogenously determined number of harvest units. As indicated in Table 16, the restricted harvest season results in harvesting of more tons of biomass than the unrestricted harvest season. Since harvested biomass feedstock stays longer in storage the total annual storage losses are greater with a restricted harvest season hence the need to harvest more biomass than the unrestricted harvest season. The trend in Figure 101 is similar to that of Figure 95 in that with an unrestricted harvest season the quantity of harvested biomass would increase steadily

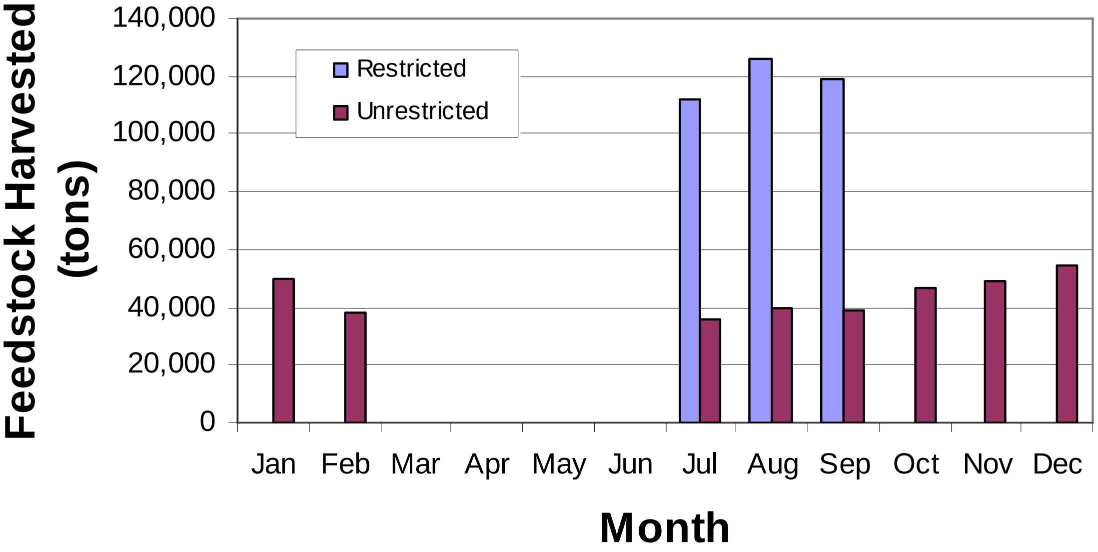


**Figure 101.Estimated quantity of feedstock harvested per month for a 1,000 tons per day biorefinery from feedstock produced on CRP grasslands in Kansas, Oklahoma and Texas from both a restricted harvest season and an unrestricted harvest season**

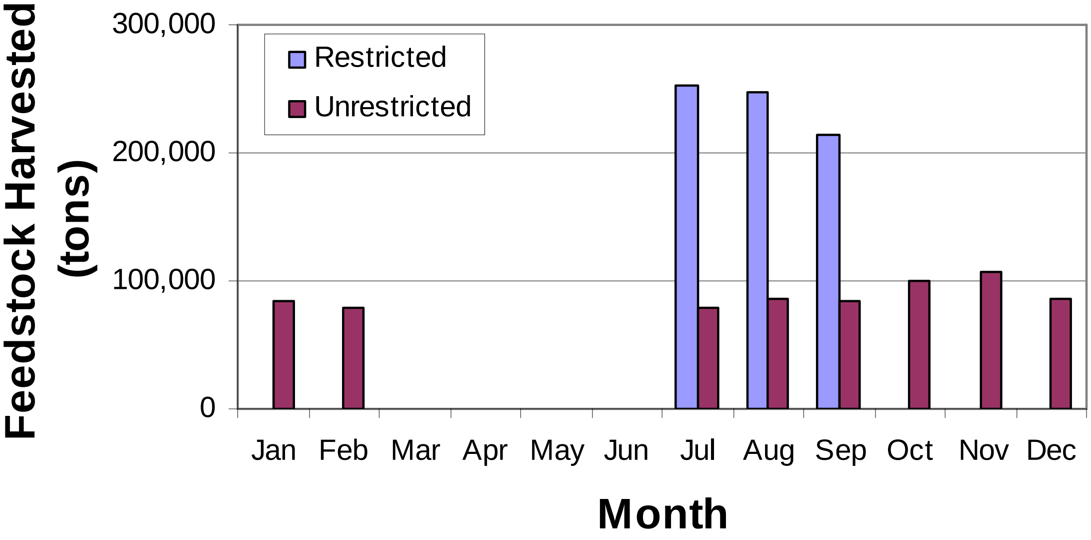


Figure 102.Estimated quantity of feedstock harvested per month for a 2,000 tons per day biorefinery from feedstock produced on CRP grasslands in Kansas, Oklahoma and Texas from both a restricted harvest season and an unrestricted harvest season

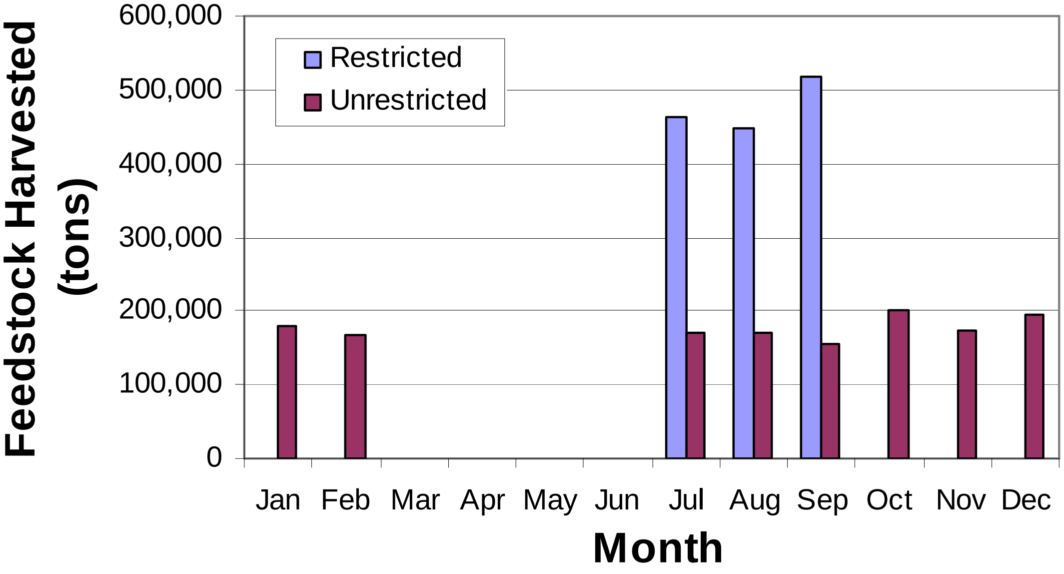


Figure 103.Estimated quantity of feedstock harvested per month for a 4,000 tons per day biorefinery from feedstock produced on CRP grasslands in Kansas, Oklahoma and Texas from both a restricted harvest season and an unrestricted harvest season

from the month of July until December and decline in the months of January and February. For the restricted harvest season, Figure 101 shows that most biomass would be harvested in the months of August and September. Figure 102 shows that with an unrestricted harvest season, quantities of biomass harvested would increase steadily from the month of July through November and decline in the months of December through February the following year. But for the restricted harvest season the quantities harvested would be highest in the first month of harvesting and steadily decline in August and September. Figure 103 shows that when the harvesting season is restricted, most of the biomass would be harvested in the last harvest month of September. On the other hand with an unrestricted harvest season, biomass would be harvested in steady quantities.

Figure 104 shows the quantities of biomass feedstock harvested for each plant size by feedstock type for both a restricted harvest season and an unrestricted harvest season. The terms Cowbs and CNamixed stand for old world bluestem and mixed native grasses grown on CRP land. When the harvest season is restricted, old world bluestem is the most preferred biomass harvested of the two. This is true for all biorefinery sizes except the large plant, whose model harvests about the same quantity of both biomass feedstocks. On the other hand, when the harvest season is unrestricted mixed native grasses are the most preferred type of feedstock of the two. This is true for all biorefinery sizes. Biomass feedstock is drawn from counties in southern Kansas, all of Oklahoma and the Texas Panhandle.

The State of Oklahoma was divided into five regions, namely: Panhandle, Northwest, Southwest, Northeast, and Southeast. During establishment of CRP grasses the whole of Kansas CRP lands were established to mixed native grasses only, while

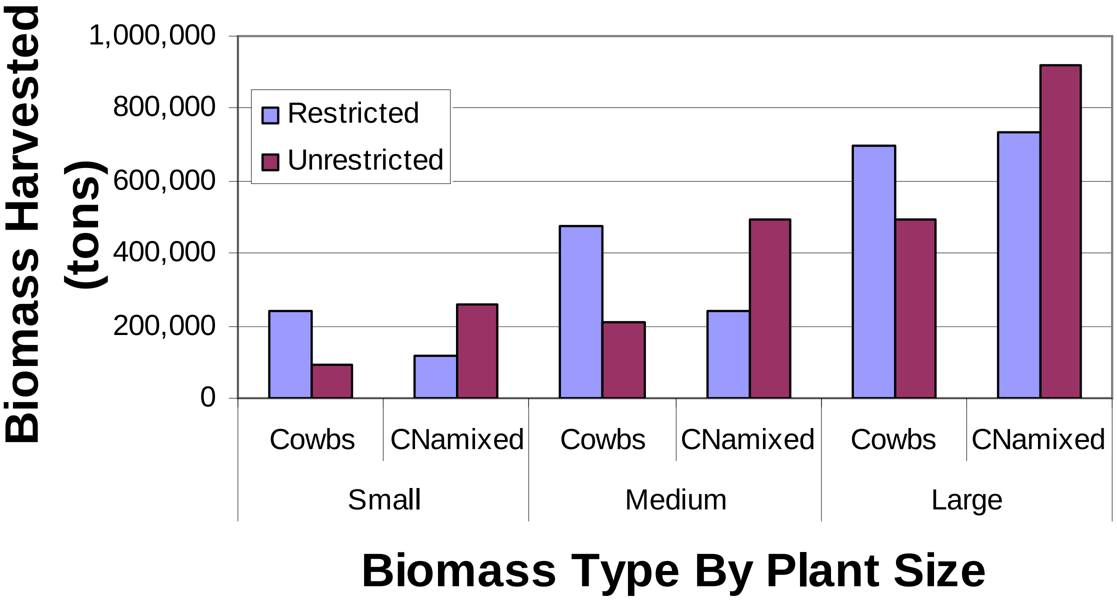


**Figure 104.Estimated quantity of feedstock harvested by biomass type and plant size for a 1,000, 2,000 and 4,000 tons per day biorefinery from feedstock produced on CRP grasslands in Kansas, Oklahoma and Texas from both a restricted harvest season and an unrestricted harvest season**

those of Oklahoma and Texas were established to a mixture of old world bluestem and mixed native grasses with old world bluestem dominating mixed native grasses. As shown in Figure 104, when the harvest season is restricted the most preferred biomass feedstock is old world bluestem and when the harvest season is unrestricted mixed native prairies are the most preferred biomass feedstock.

## Comparison of LCB Feedstock Stored between Restricted and Unrestricted Models

Figures 105, 106, and 107 include charts of the estimated quantities of feedstock stored per month at field sites for a 1,000, 2,000 and 4,000 tons per day biorefinery for both the restricted and the unrestricted harvest season. If the harvest season is restricted, replenishment of storage reserves begins with the first permissible harvest month of July. Harvest and increase of field storage inventory continues throughout August and

September. At the end of September, when by policy the harvest must cease, the combined field and biorefinery storage inventory must be sufficient to provide feedstock until harvest may be resumed in the following July. Feedstock is removed from field storage until the end of June when inventory of both field storage and storage at the biorefinery are reduced to zero.

For the unrestricted harvest window, field inventory storage increases more gradually from July through February (Figures 105 through 107). The maximum quantity of required field storage for the unrestricted scenario is less than half of that required for the restricted harvest window. This results in higher in-field storage costs for the restricted than for the unrestricted harvest season (Table 16).

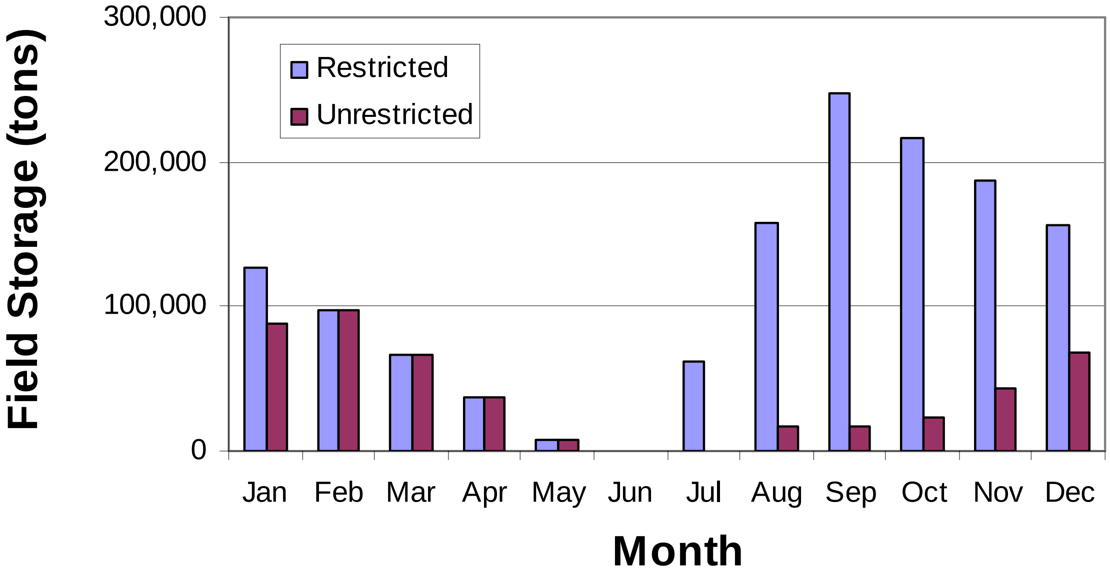


**Figure 105.Estimated quantity of feedstock stored per month in the field for a 1,000 tons per day biorefinery from feedstock produced on CRP grasslands in Kansas, Oklahoma and Texas from both a restricted harvest season and an unrestricted harvest season**

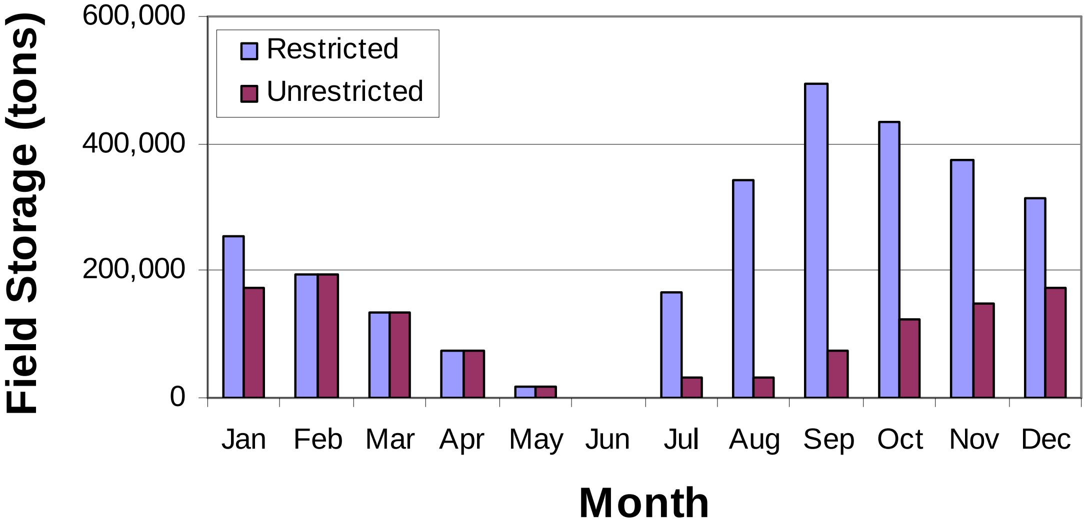


**Figure 106.** Estimated quantity of feedstock stored per month in the field for a 2,000 tons per day biorefinery from feedstock produced on CRP grasslands in Kansas, Oklahoma and Texas from both a restricted harvest season and an unrestricted harvest season

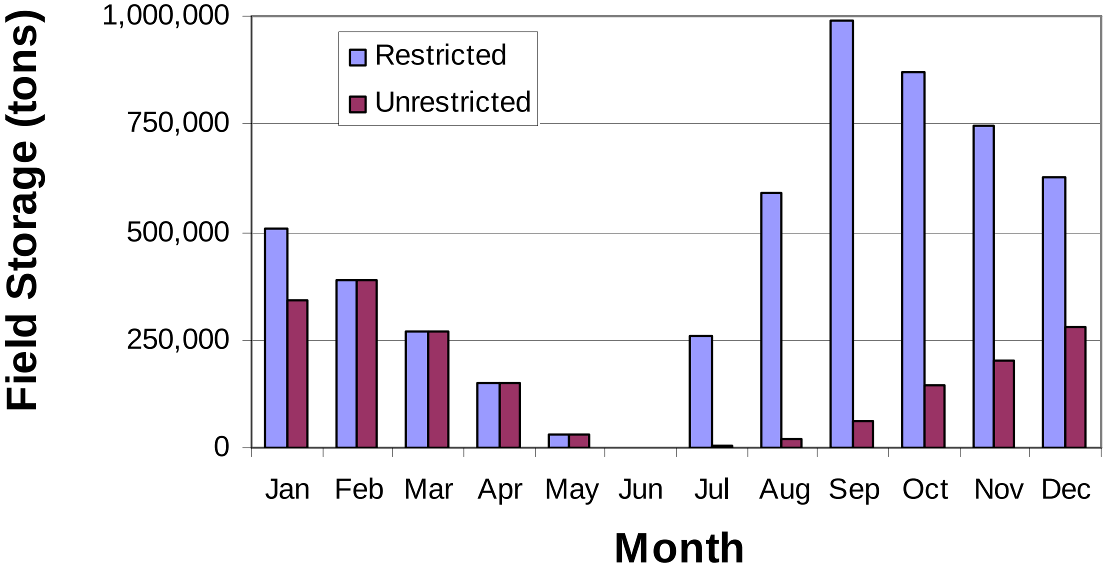


**Figure 107.** Estimated quantity of feedstock stored per month in the field for a 4,000 tons per day biorefinery from feedstock produced on CRP grasslands in Kansas, Oklahoma and Texas from both a restricted harvest season and an unrestricted harvest season

Figures 108 through 110 present charts of biomass feedstock storage at the biorefinery for a 1,000, 2,000 and 4,000 dry tons per day plant. The charts present comparison of storage inventory for the restricted and unrestricted harvest season for the three different plant sizes. In all three cases the restricted harvest season model stores cumulatively more LCB feedstock at the biorefinery than the unrestricted harvest season model. For most months storage is used to the maximum capacity.

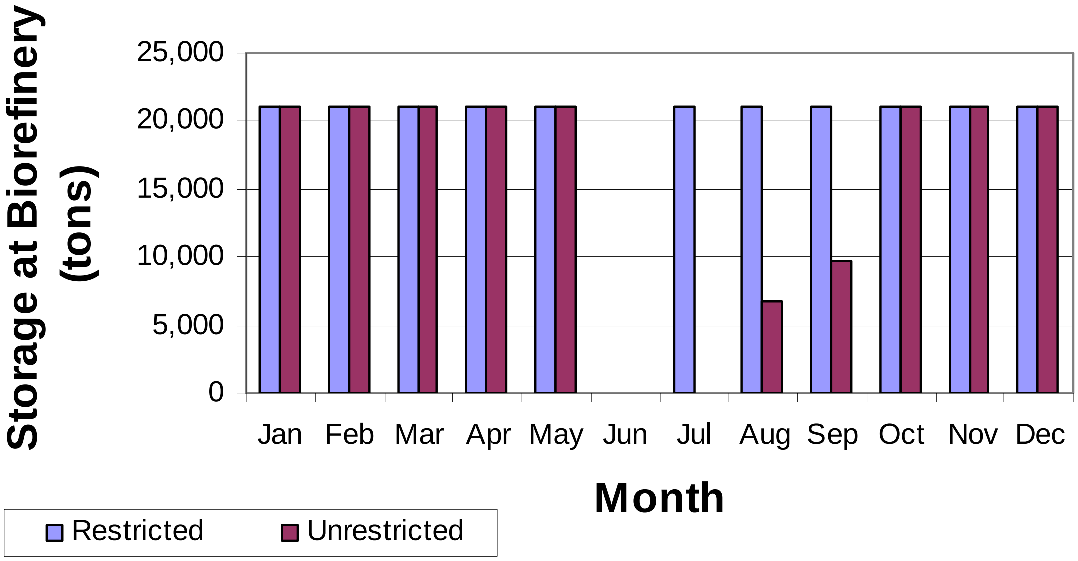


**Figure 108.** Estimated quantity of feedstock stored per month at the biorefinery for a 1,000 tons per day biorefinery from feedstock produced on CRP grasslands in Kansas, Oklahoma and Texas from both a restricted harvest season and an unrestricted harvest season

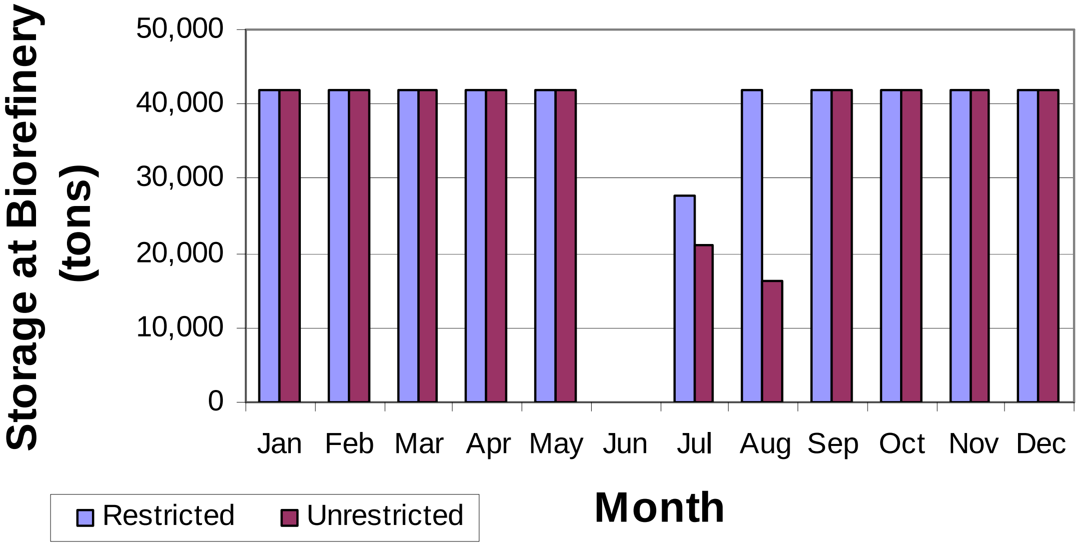


**Figure 109.** **Estimated quantity of feedstock stored per month at the biorefinery for a 2,000 tons per day biorefinery from feedstock produced on CRP grasslands in Kansas, Oklahoma and Texas from both a restricted harvest season and an unrestricted harvest season**

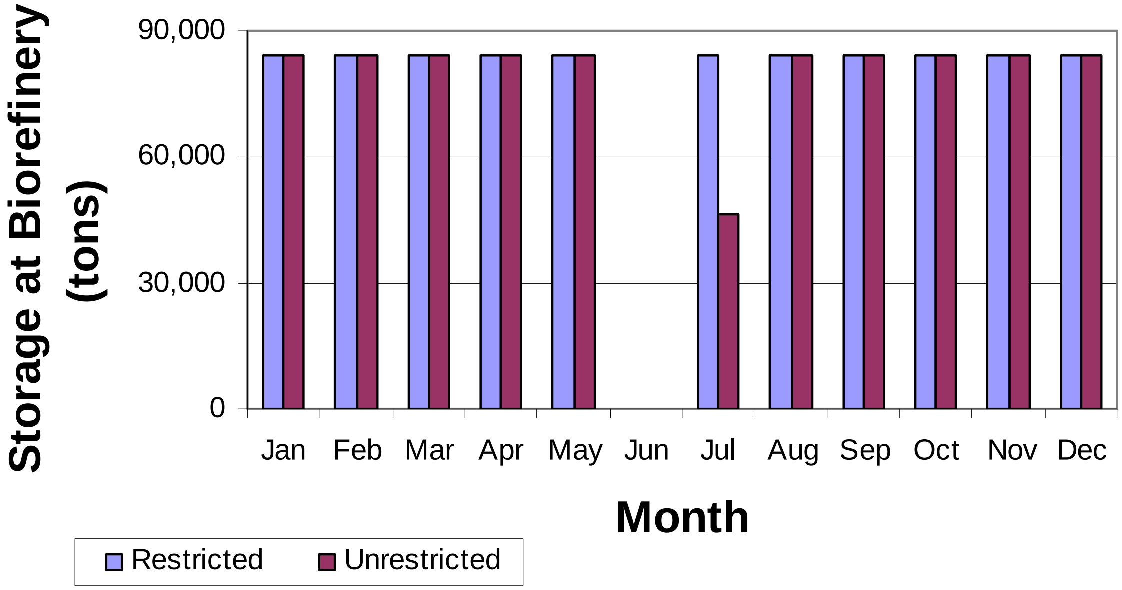


**Figure 110.** **Estimated quantity of feedstock stored per month at the biorefinery for a 4,000 tons per day biorefinery from feedstock produced on CRP grasslands in Kansas, Oklahoma and Texas from both a restricted harvest season and an unrestricted harvest season**

**Comparison of Biomass Shipments between Restricted and Unrestricted Models**

Figures 111 through 113 are charts presenting biomass feedstock shipments from the field and in-field storage to a biorefinery optimally located in Oklahoma. The charts show that shipments of biomass feedstock begin from the field and field storage to the plant with the month of July for both a restricted harvest season and an unrestricted harvest season. Steady shipments continue throughout the year with last shipment being done in the month of June. No significant differences exist between the quantities of biomass shipped from the field and field storage for both a restricted harvest season and unrestricted harvest season.

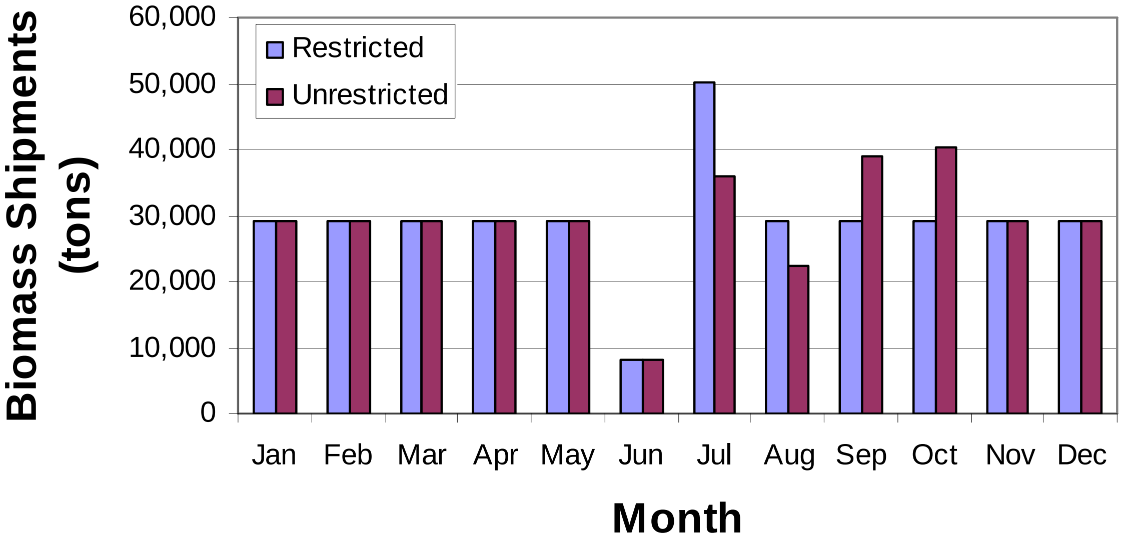


**Figure 111.Estimated quantity of feedstock shipped per month to a 1,000 tons per day biorefinery from CRP grasslands in Kansas, Oklahoma and Texas from both a restricted harvest season and an unrestricted harvest season**

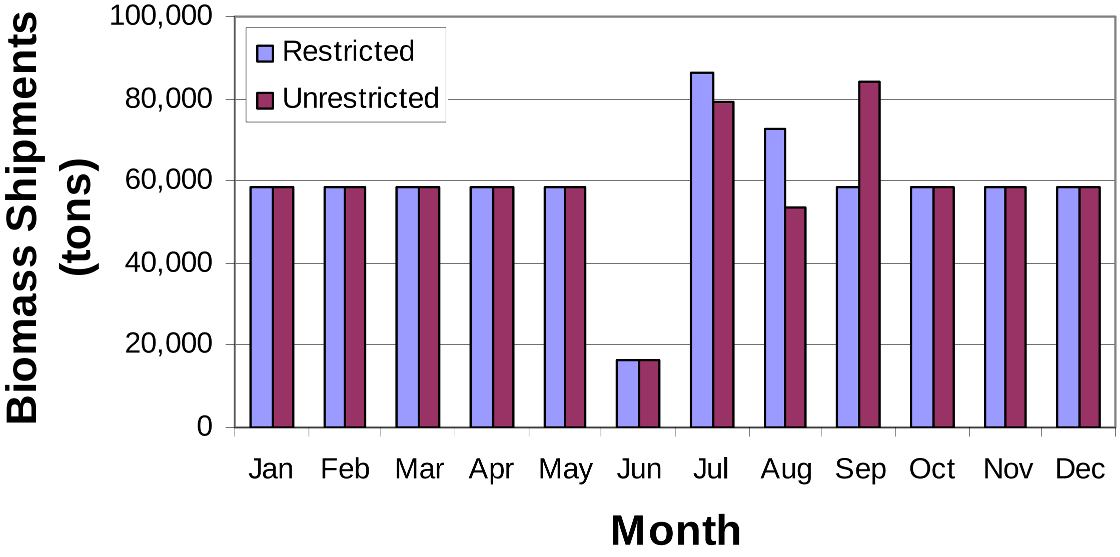


Figure 112.Estimated quantity of feedstock shipped per month to a 2,000 tons per day biorefinery from CRP grasslands in Kansas, Oklahoma and Texas from both a restricted harvest season and an unrestricted harvest season

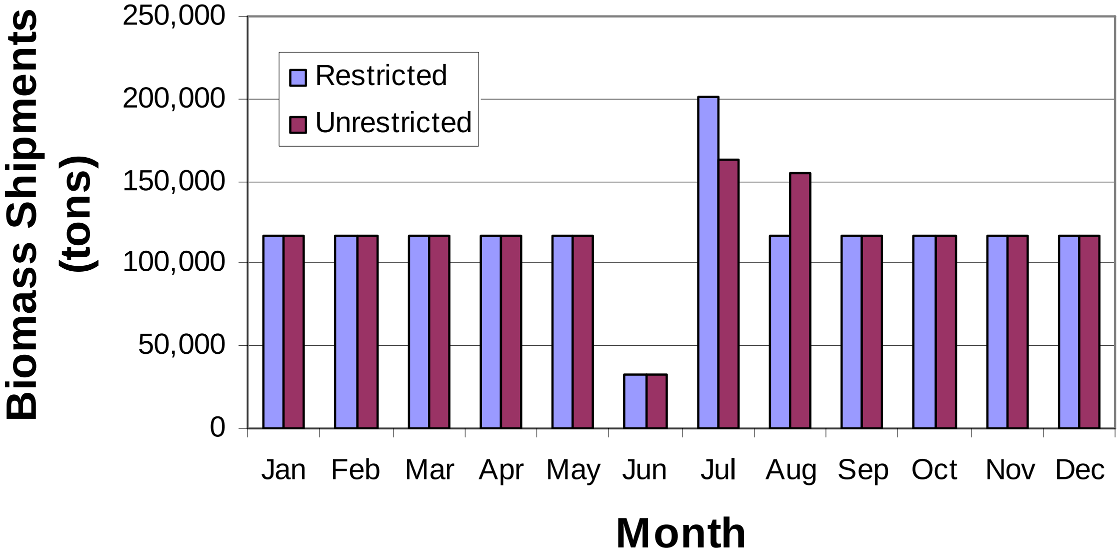


Figure 113. Estimated quantity of feedstock shipped per month to a 4,000 tons per day biorefinery from CRP grasslands in Kansas, Oklahoma and Texas from both a restricted harvest season and an unrestricted harvest season

## Comparison of the Cost to Deliver a Ton of Biomass to a Biorefinery

Figure 114 includes a chart that compares the cost to deliver a ton of LCB feedstock to a biorefinery optimally located in Oklahoma. The model shows that the base model attains the lowest cost to deliver a ton of biomass to a biorefinery. This is followed by the crop residue model and then the restricted harvest season model of the CRP (Conservation Reserve Program) land. The total cost to deliver a ton of biomass feedstock to a biorefinery for the base model is $35.37 per ton, for the crop residue model is $53.77 per ton and for the CRP model is $57.83 per ton. While the crop residue and CRP models assume few biomass feedstock species, the base model assumes a variety of biomass species that mature at different periods of the year. This enables the base model to continue harvesting throughout the year thereby minimizing the per ton harvest cost, storage cost and shipment cost. Furthermore crop residues can only be harvested in four of the twelve months in a year and the CRP land is restricted to a cumulative harvest season of 87 days in the region included in this study.

By having a restricted harvest season in the crop residue and CRP models, the optimal number of harvest units increased thereby increasing the harvest cost. Secondly, since the biorefinery plant has to operate throughout the year, the short harvest period also resulted in keeping large quantities of biomass feedstock in storage for a longer period than in the base model thereby incurring higher storage costs. The short harvest season in the crop residue and CRP model also resulted in higher transportation cost. This was so because by storing large quantities of LCB feedstock for the whole year higher storage losses were incurred than in the base model. This required that more biomass, over and above the quantity required by the biorefinery, had to be harvested and transported to storage facilities in the field and at the biorefinery to account for storage losses.

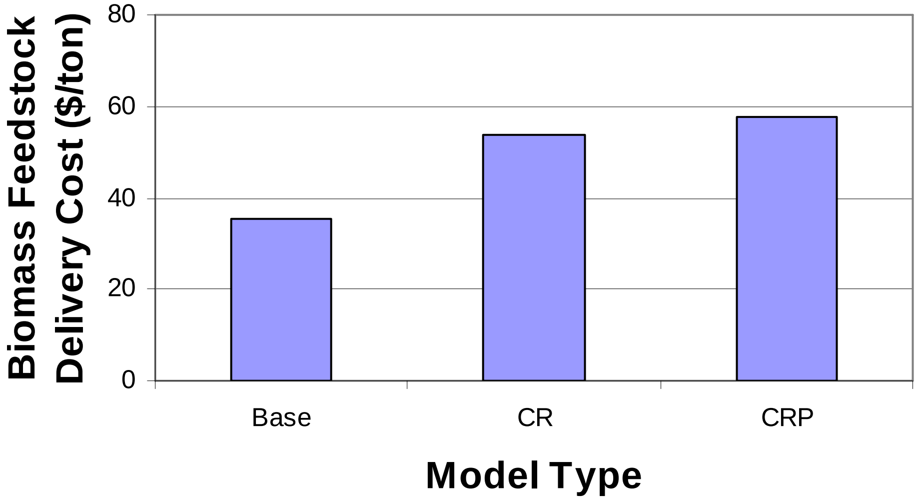


**Figure 114.** **Comparison of biomass feedstock delivery cost per ton among the three main models in this study: the base model (endogenous harvest cost model), the crop residue model (RES100-60) and the conservation reserve program (CRP) land restricted harvest season model**

# CHAPTER VI

# SUMMARY AND CONCLUSIONS

A biorefinery is a facility that converts (refines) biological material (biomass) into products. Research programs to develop technology that will enable converting lignocellulosic biomass (LCB) feedstock into useful products are underway at government, university, and private facilities. The economic success of an unsubsidized LCB biorefinery will depend upon its ability to either produce (a) unique valuable products or to produce (b) products more cheaply than fossil-based substitutes.

Experience from conventional crude oil refineries and electric power generating plants suggest that (a) the cost of delivered feedstock is a major component of the cost to produce products, and (b) size economies are very important in the production of bulk commodities. 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. While the data suggest that in the absence of subsidies or other government interventions, it would be very difficult for an LCB biorefinery to compete with a conventional crude oil refinery in the production of bulk commodities such as liquid fuels, it is possible that LCB may be used to produce unique valuable products. And, feedstock cost is expected to be an important component of total production costs.

A major potential advantage of LCB biorefining technology is that a variety of feedstock, 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 feedstock 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.

The infrastructure for production, harvest, storage, transportation, and price risk management of corn grain is well developed. 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.

Prior to Tembo, most models of LCB production, harvest, and transportation included a single point estimate of the harvest cost per ton or per acre. While this may be a reasonable approach if the feedstock is corn grain, it may be less so for a feedstock such as LCB for which a harvesting infrastructure does not exist. The ability to economically produce ethanol and other bioproducts from low-cost LCB will be key to making these products economically competitive. It is, therefore, important to effectively capture the procurement, harvesting and transportation costs of LCB in the project appraisal of an LCB biorefinery system.

The focus of this research was to determine the cost to deliver a steady flow of LCB feedstock throughout the year to a biorefinery optimally located in Oklahoma. Specific objectives included: (i) to determine how the method of modeling harvest and procurement cost changes the cost to deliver a ton of LCB (from crop residue, indigenous native prairies, improved pastures, Conservation Reserve Program (CRP) land, dedicated switchgrass) to a biorefinery that has the capacity to process 1,000, 2,000, or 4,000 dry tons per day; (ii) to determine the cost to deliver a ton of crop residue (wheat straw and corn stover) to 1,000, 2,000, or 4,000 dry tons per day biorefineries; (iii) to determine the cost to deliver a ton of LCB from CRP land to biorefineries, optimally located in Oklahoma, that have capacity to process either 1,000 or 2,000, or 4,000 dry tons per day.

In this study a multi-region, multi-period mixed integer mathematical programming model was developed to address the objectives. This study differs from prior studies in the following respects (i) it incorporates harvest unit as an integer and endogenously chosen activity; (ii) it incorporates an estimate of the expected number of harvest days per month based upon historical weather patterns; (iii) it assumes that the farmer/landowner can either be paid a fixed rate per ton for material harvested or be paid a fixed rate per acre for the rights to harvest the material on CRP land; (iv) biomass feedstock storage costs are charged on a per ton basis regardless of the number of months the feedstock is kept in storage; (v) the model includes alternative feedstock and harvest capacity constraints determined by the number of harvest days per month and the endogenously determined number of harvest units; (vi) the model breaks the year into 12 discrete periods (months) enabling a flow of feedstock to a biorefinery and recognizes that the expected dry matter yield of species depends upon the time (month) of harvest and that storage losses will occur and depend upon location of storage and time of storage.

To achieve the first objective, 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. In the exogenous harvest cost model the total cost to deliver a ton of biomass was $35.37 compared to $34.91 for the endogenous harvest cost model. The optimal number of harvest units for the endogenous harvest cost model was 26 requiring an average investment of about $15.3 million. For the exogenous harvest cost model, to harvest the July biomass quantity, 53 harvest units would be required at more than twice as much the average investment as that of the endogenous harvest cost i.e. $31.3 million. Furthermore, by modeling harvest costs as an exogenous variable the optimal plant location changes from Canadian county to Custer county. The location change due to changes in modeling affects the allocation of resources such as acres and tons harvested across the harvest periods (months) as well as labor.

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 more nearly capture the true harvest cost and give more reliable results than an alternative model that assumes an exogenous harvest cost per ton. LCB harvesting for biorefinery production requires machinery and harvest crews with capacity constraints.

In the base model it was observed that as the plant size increased so did the estimated expected cost to deliver a ton of LCB feedstock to a biorefinery. The base model is sensitive to the number of available harvest days. Changes in weather can sometimes adversely affect field operations including harvesting of LCB. A reduction by half in the number of monthly harvest days increased the total cost to deliver feedstock by $10.33 per ton and also increased the average investment in harvest machinery by $14.2 million. The harvest days reduction shifted the optimal location of the biorefinery from Canadian to Custer counties. An increase in the acquisition cost of biomass from $8.87/ton to $16.50/ton and the cost of the harvesting from $10.72/ton to $15.47/ton also shifted the optimal location of the plant from Canadian county to Custer county. But by doubling the purchase cost of biomass from $10/ton to $20/ton the total cost to deliver feedstock to a biorefinery increased by $8.35 per ton. Increasing the cost of a harvest unit from $580,000/year to $870,000/year resulted in increasing the total cost to deliver feedstock to the biorefinery by $5.17 per ton. Clearly, available harvest days are an important component in the LCB biorefinery industry. Furthermore, the proportion of harvestable acres in each region is another important variable. Increasing the proportion of harvestable acres in each region from 10% to 35% reduced the expected cost to deliver a ton of LCB by about $4.00 per ton.

To solve for the second objective, a model that assumed harvesting 60% of tons of crop residues on each acre and three sensitivity analyses were analyzed. Unlike other feedstock, crop residues can only be harvested in a period of four months from June to July for wheat straw and September to October for corn stover. In the RES 100-60 model (the model in which 60% of crop residue tons on every acre are harvested) the total cost to deliver a ton of crop residues to a biorefinery was $53.77 per ton. Compared to the base model which had multiple feedstock the total cost to deliver biomass feedstock to a biorefinery was $35.37 per ton, which is $19.21 per ton less. The optimal plant was a large size located in Custer county in Northwest region. The crop residue model (RES 100-60) was sensitive to all the three sensitivity analyses done but it was more sensitive to available acres that provide crop residues. In the RES 25-60 scenario, in which the available acres were reduced to 25%, the model chose a medium plant. When available acres were reduced to 50% the model chose a large plant located in Custer county but the total cost to deliver feedstock increased by $7.17 per ton from the RES 100-60 scenario result of $53.77.

The third objective involved the use of CRP land for the production of LCB feedstock for use in biorefinery. The Farm Security and Rural Investment Act of 2002 enabled managed harvest of CRP grassland acres for biorefinery feedstock use. Three biorefinery sizes (either 1,000 or 2,000 or 4,000 tons of biomass per day) were considered for both of two harvest season lengths (either the restricted harvest season or an unrestricted harvest season).

CRP acres are dispersed, expected yields are relatively low, and harvest is limited by policy to an average of once in three years. The model was constrained to harvest no more than 25 percent of the CRP enrolled acres per county annually. It was determined that the estimated cost to deliver a flow of feedstock to a biorefinery ranged from $28 to $59 per ton depending upon the size of the biorefinery and the length of the harvest season. Increasing biorefinery feedstock requirements from 1,000 to 4,000 tons per day increases required transportation distances and increases the expected delivery cost by $13.83 per ton for the restricted-harvest model and by $8.76 for the unrestricted harvest model. The estimated average one-way feedstock transportation distance ranged from 63 to 147 miles.

Given the underlying assumptions of the model, for the case study region, restricting the harvest window imposes a rather substantial cost on the industry. The policy restricted harvest window more than doubles the expected harvest cost and expected field storage costs. Restricting the harvest window increases the cost to deliver a ton of biomass by \$17 to \$22 per ton. For the biomass biorefinery industry to develop and be economically feasible, it would be prudent for the policy makers to determine a separate harvest period for biomass required for biorefinery processing. The logical harvest season for native grasses for biorefinery use is outside the nesting and brood season for grassland birds. A managed harvesting season could be designed to be in accordance with a well stipulated conservation plan and in line with long-term protection of existing grasslands. Such a policy would not only benefit the environment and natural habitat for wildlife but would also be in the interest of the biorefinery industry for sustainable and continuous flow of biomass feedstock to the biorefinery.

Based on this study an LCB biorefinery business would develop in concert with well coordinated biomass feedstock harvest units. The harvest units would be managed either by the biorefinery industry itself or by a private company. A total of 26 harvest units would be purchased at an average investment of \$15.34 million. These harvest units would result in a per ton harvest cost of \$10.72. It would be necessary to have a continuous and reliable flow of biomass feedstock from the field to the biorefinery. This would entail taking advantage of a variety of biomass feedstock species that mature at different periods during the year. A total of seven biomass feedstock species would be used including wheat straw, corn stover, old world bluestem, bermuda grass, native tall grass, native short grass, and native grass. A harvest season of nine months would be more economical since it would minimize the cost to deliver LCB to a biorefinery. Developing an LCB biorefinery industry having in mind one or two sources or types of biomass (e.g. crop residues only or CRP source only) may result in high cost to deliver a ton of feedstock and lack of competitiveness by the LCB biorefinery industry. The seven biomass feedstocks would be hauled from a radius of 106 miles to a large size biorefinery. The biorefinery would be located in Canadian county and would be used at full capacity. About 946,000 acres would be harvested annually supplying 1.4 million tons of biomass feedstock.

## Limitations of Current Research

The main objective of this research was to determine the cost to deliver a continuous flow of biomass feedstock to either a 1,000, 2,000, or 4,000 tons per day biorefinery optimally located in Oklahoma. The multi-period, multi-region mixed integer mathematical programming model used in this study is a deterministic model. Therefore the estimated expected cost to deliver a ton of LCB feedstock to a biorefinery of $35.37 should be considered a lower bound. The expected cost would be higher depending on stochastic variables like LCB yields and available harvest days in each month. The sensitivity analyses done on a few variables showed that the estimated expected cost to deliver a ton of LCB to a biorefinery may be adversely affected by changes in some of these variables.

The introduction of an endogenously determined harvest unit in this model seem to provide results that may give reliable policy direction. Further research on the harvest capacity and annual operating cost of the harvest unit would be very important to provide concrete information. This study has shown that the model results are sensitive to the cost of a harvest unit as well as the harvest capacity.

A comprehensive research needs also to be done to obtain better estimates of number of days available in each month when harvesting can be successfully done. This reliable information of monthly harvest days can then be incorporated into the model for better policy direction. This study determined that model results were sensitive to available monthly harvest days. Since the LCB biorefinery industry would involve field activities, the effects of weather on the industry is of paramount importance.

As observed in the literature review there are varying estimates in literature on the prices that a farmer need to charge for a ton of biomass especially if the biomass is crop residues. The acquisition cost of biomass feedstock has varied from about \$6.00 per ton in some literature to as high as about \$40.00 per ton in others. The variation is attributed to variations in assumptions. When biomass feedstock is assumed as a good source of fertilizer or as a control to erosion its value has been high. Equally when the livestock industry has been assumed as a competitor on the same biomass feedstock its value has also been high. This study determined that the cost to deliver a continuous flow of a ton of biomass feedstock to a biorefinery would be affected by the per ton biomass acquisition cost. Further research that would determine the per ton value of biomass, preferably varying by type of species, would be a valuable contribution.

The length of a harvest season and the proportion of biomass acres or tons that can be harvested are also important factors in determining the cost to deliver a ton of biomass feedstock to a biorefinery. When the proportion of harvested acres was increased twice in the base model the expected cost to deliver a ton of LCB to a biorefinery reduced. The reduction in the expected cost to deliver a ton of LCB to a biorefinery was higher the larger the proportion of harvestable acres in each region. Secondly, if land under CRP will be a source of biomass feedstock for an LCB biorefinery, as is expected, a reasonable and well-thought harvest season for biorefinery purposes has to be determined. The model in this study has shown sensitivity to the length of a harvest season. Furthermore, the proportion of acres and/or tons harvested have been determined in this study to affect the total cost to deliver a ton of biomass feedstock to a biorefinery. Determining reliable figures on these issues would be important to the study of the economics of an LCB biorefinery industry.

There are a number of LCB biorefinery technologies currently under research. These include (1) thermo-chemical such as: combustion, gasification, pyrolysis, liquefaction and hydro-thermal upgrading (2) bio-chemical such as: fermentation and anaerobic digestion. Further research on the various conversion processes available could be an added knowledge. Data would be collected on the costs associated with each conversion technology and the products and by products produced. The data would then be added to the model to determine which technologies are cost-effective and economically more competitive.

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# APPENDICES

# APPENDIX A

## Tembo's Assumptions about Harvest Structure and Cost

**Table 17. Harvest Machinery Assumptions and Costs ($/acre) for Corn Stover and All Forage Grasses**

| Organization | | Implement Assumption | | | Tractor Assumptions | | |
|---|---|---|---|---|---|---|---|
| Structure/Activity | Implement used | Width (feet) | Speed (mph) | Purchase Price ($) | Horsepower | Purchase Price ($) | Activity Cost ($/acre) |
| Vertically integrated[b] | | | | | | | |
| Cutting | Disk mower conditioner | 9.8 | 7.0 | 18,500 | 75 | 30,000 | 5.05 |
| Raking | Twin-wheel rake | 18.0 | 6.0 | 6,000 | 75 | 30,000 | 2.22 |
| Baling | Large square baler | 30.0 | 7.0 | 65,000 | 150 | 61,000 | 5.05 |
| Total harvest cost vertically integrated structure | | | | | | | 12.32 |
| Atomistic[c] | | | | | | | |
| Cutting | Rotary disk mower | 9.2 | 7.0 | 6,000 | 75 | 30,000 | 4.66 |
| Raking | Twin-wheel rake | 18.0 | 6.0 | 6,000 | 75 | 30,000 | 3.22 |
| Baling | Large round baler | 30.0 | 5.0 | 18,500 | 150 | 61,000 | 8.41 |
| Total harvest cost atomistic structure | | | | | | | 16.29 |

[a] Forage grasses include native prairies (tall, mixed, short), bermudagrass, and tall fescue
[b] Assuming 5,000 acres are harvested annually
[c] Assuming the individual farmer harvests an average of 500 acres each year
Source: Adapted from Tembo (2000).

### Table 18. Harvest Machine Assumptions and Costs ($/acre) for Wheat Straw

| | Implement Assumption | | | | Tractor Assumptions | | |
|---|---|---|---|---|---|---|---|
| Organization Structure/Activity | Implement used | Width(feet) | Speed(mph) | Purchase Price ($) | Horsepower | Purchase Price ($) | Activity Cost ($/acre) |
| Vertically integrated[a] | | | | | | | |
| Cutting[b] | n/a | n/a | n/a | n/a | n/a | n/a | n/a |
| Raking | Twin-wheel rake | 18.0 | 6.0 | 6,000 | 75 | 30,000 | 2.22 |
| Baling | Large square baler | 30.0 | 7.0 | 65,000 | 150 | 61,000 | 5.05 |
| Total harvest cost vertically integrated structure | | | | | | | 7.27 |
| Atomistic[c] | | | | | | | |
| Cutting[b] | n/a | n/a | n/a | n/a | n/a | n/a | n/a |
| Raking | Twin-wheel rake | 18.0 | 6.0 | 6,000 | 75 | 30,000 | 3.22 |
| Baling | Large round baler | 30.0 | 5.0 | 18,500 | 150 | 61,000 | 8.41 |
| Total harvest cost atomistic structure | | | | | | | 11.63 |

[a] Assuming 5,000 acres are harvested annually
[b] Wheat straw is cut during wheat grain harvesting
[c] Assuming the individual farmer harvests an average of 500 acres each year
Source: Adapted from Tembo (2000).

**Table 19. Harvest Machinery Assumptions and Costs ($/acre) for Switchgrass**

| | Implement Assumption | | | | Tractor Assumptions | | |
|---|---|---|---|---|---|---|---|
| Organization Structure/Activity | Implement used | Width(feet) | Speed(mph) | Purchase Price ($) | Horsepower | Purchase Price ($) | Activity Cost ($/acre) |
| Vertically integrated[b] | | | | | | | |
| Cutting | Disk mower conditioner | 9.8 | 4.0 | 18,500 | 75 | 30,000 | 7.89 |
| Raking | Twin-wheel rake | 9.0 | 4.0 | 2,000 | 75 | 30,000 | 5.50 |
| Baling | Large square baler | 9.8 | 7.0 | 65,000 | 150 | 61,000 | 10.90 |
| Total harvest cost vertically integrated structure | | | | | | | 24.29 |
| Atomistic[c] | | | | | | | |
| Cutting | Rotary disk mower | 9.2 | 4.0 | 6,000 | 75 | 30,000 | 7.59 |
| Raking | Twin-wheel rake | 9.0 | 4.0 | 2,000 | 75 | 30,000 | 5.82 |
| Baling | Large round baler | 9.8 | 5.0 | 18,500 | 150 | 61,000 | 15.92 |
| Total harvest cost atomistic structure | | | | | | | 29.33 |

[a] Machine specifications are adjusted to fit the high yields attained with switchgrass.
[b] Assuming 5,000 acres are harvested annually.
[c] Assuming the individual farmer harvests an average of 500 acres each year.
Source: Adapted from Tembo (2000).
.

**Table 20. Biomass Production and Opportunity Costs in U.S. $/Acre/Year**

| | Cost By Category | | | |
|---|---|---|---|---|
| Feedstock Species | Establishment Costs | Maintenance Costs | Land Rent | Biomass Opportunity Cost |
| Wheat Straw | 0.00 | 0.00 | 0.00[b] | 10.00 |
| Corn Stover | 0.00 | 0.00 | 0.00[b] | 20.00 |
| Old World Bluestem | 0.00 | 3.00 | 40.00 | 0.00 |
| Native Tall | 0.00 | 0.00 | 20.00 | 0.00 |
| Native Mixed | 0.00 | 0.00 | 20.00 | 0.00 |
| Native Short | 0.00 | 0.00 | 20.00 | 0.00 |
| Bermudagrass | 0.00 | 3.00 | 40.00 | 0.00 |
| Tall Fescue | 0.00 | 3.00 | 40.00 | 0.00 |
| Switchgrass | 11.22 | 3.00 | 60.00[a] | 0.00 |

[a] Because no land was allocated to switchgrass production in the state at the time of the study, any acre of switchgrass that came into the basis would need to displace some existing cropping activity.  Hence the high land rent on switchgrass.

[b] Zero land rent is charged to wheat straw and corn stover because they are crop residues and the true land rent is already accounted for in the grain production activities.

Sources:  Adapted from Tembo (2000).

# APPENDIX B

## GAMS/CPLEX Code for the Base Model

## The Endogenous Harvest Cost Model

```
$OFFUPPER OFFSYMXREF OFFSYMLIST OFFUELLIST OFFUELXREF
OPTIONS LIMROW=0, LIMCOL=0;
OPTION OPTCR = 0.0000;
*OPTION SYSOUT = ON;
OPTION SOLPRINT=OFF;
OPTION RESLIM=1000000;
OPTION ITERLIM=5000000;
SETS
 C Counties
   /Adair, Alfalfa, Atoka, Beaver, Beckham, Blaine, Bryan, Caddo,
    Canadian, Carter, Cherokee, Choctaw, Cimarron, Clevelan, Coal,
    Comanche, Cotton, Craig, Creek, Custer, Delaware, Dewey, Ellis,
    Garfield, Garvin, Grady, Grant, Greer, Harmon, Harper, Haskell,
    Hughes, Jackson, Jeffers, Johnston, Kay, Kingfish, Kiowa,Latimer,
    LeFlore, Lincoln, Logan, Love, Major, Marshall, Mayes, McClain,
    McCurt, McIntosh, Murray, Muskogee, Noble, Nowata, Okfuskee,
    Oklahoma, Okmulgee, Osage, Ottawa, Pawnee, Payne, Pittsbur,
    Pontotoc, Pottawat, Pushmata, RogerMil, Rogers, Seminole,
    Sequoyah,Stephens, Texas, Tillman, Tulsa, Wagoner, Washing,
    Washita, Woods, Woodward/

 I(C)  Biomass supplying counties
   /Adair, Alfalfa, Atoka, Beaver, Beckham, Blaine, Bryan, Caddo,
    Canadian, Carter, Cherokee, Choctaw, Cimarron, Clevelan, Coal,
    Comanche, Cotton, Craig, Creek, Custer, Delaware, Dewey, Ellis,
    Garfield, Garvin, Grady, Grant, Greer, Harmon, Harper, Haskell,
    Hughes, Jackson, Jeffers, Johnston, Kay, Kingfish, Kiowa,
    LeFlore, Lincoln, Logan, Love, Major, Marshall, Mayes, McClain,
    McCurt, McIntosh, Murray, Muskogee, Noble, Nowata, Okfuskee,
    Oklahoma, Okmulgee, Osage, Ottawa, Pawnee, Payne, Pittsbur,
    Pontotoc, Pottawat, RogerMil, Rogers, Seminole, Sequoyah,
    Stephens, Texas, Tillman, Tulsa, Wagoner, Washing, Washita,
    Woods, Woodward/

 J(C)  Processing plant locations
   /Pontotoc, Jackson, Washing, Canadian, Garfield, Texas,
    Comanche, Okmulgee, Payne, Woodward, Custer/

 R Geographical Regions of Oklahoma
   /PANHAND, NWEST, NEAST, SWEST, SEAST/

 IR(I,R) Counties by geographical region
   /(Beaver, Cimarron, Texas).PANHAND, (Alfalfa, Blaine, Canadian,
     Custer, Dewey, Ellis, Garfield, Grant, Harper, Kingfish, Logan,
     Major, Oklahoma, RogerMil, Woods, Woodward).NWEST,(Adair,
     Cherokee, Craig, Creek, Delaware, Kay, Lincoln, Mayes, Muskogee,
     Noble, Nowata, Okfuskee, Okmulgee, Osage, Ottawa, Pawnee, Payne,
     Rogers, Tulsa, Wagoner, Washing). NEAST, (Beckham, Caddo, Carter,
     Clevelan, Comanche, Cotton, Garvin, Grady, Greer, Harmon, Jackson,
     Jeffers, Kiowa, Love, McClain, Stephens, Tillman, Washita).SWEST, (Atoka,
     Bryan, Choctaw, Coal, Haskell, Hughes, Johnston, LeFlore,
     Marshall, McCurt, McIntosh, Murray, Pittsbur, Pontotoc, Pottawat,
     Seminole, Sequoyah).SEAST/

 JR(J,R) Prospective plant locations by region
   /Pontotoc.SEAST, (Jackson, Comanche).SWEST, (Washing, Okmulgee, Payne).NEAST,
   (Canadian, Garfield, Woodward, Custer).NWEST, Texas.PANHAND/

 K Lignocellulosic feedstocks
   /Wheatstr, Cornstov, Cowbs, CNamixed, Natall, Namixed,
    Nashort, Iberm, Iowbs, Tfesc, Switchgr/

 CRS(K) "Crop residues and switchgrass"
   /Wheatstr, Cornstov, Switchgr/

 KF Lignocellulosic biomass differentiated by fertility program
```

```
   /Wheatst, Cornsto, Cowbst, CNmixed, Ntall, Nmixed, Nshort, Iberm50,
    Iberm100, Iberm150, Iberm200, Iowbs50, Iowbs100, Iowbs150, Iowbs200,
    Tfesc50, Tfesc100, Tfesc150, Tfesc200, Switchg/

 KKF(K,KF) Allocating fertility subactivities to biomass activities
   /Wheatstr.Wheatst, Cornstov.Cornsto, Cowbs.(Cowbst), CNamixed.CNmixed,
    Natall.Ntall, Namixed.Nmixed, Nashort.Nshort, Iberm.(Iberm50,Iberm100,
    Iberm150, Iberm200), Iowbs.(Iowbs50, Iowbs100, Iowbs150, Iowbs200),
    Tfesc.(Tfesc50, Tfesc100, Tfesc150, Tfesc200), Switchgr.Switchg/

*******************************************************************
***CR = Crop residue;     NP = Native prairies;                   *
***IP = Improved pasture; SG = Switchgrass                        *
*******************************************************************

 CA Feedstock Categories
   /CR, NP, IP, SG/

 KCA(K,CA) Mapping lignocellulosic feedstocks to feedstock categories
   /(Wheatstr, Cornstov).CR, (Natall, Namixed, Nashort, CNamixed).NP,
    (Cowbs, Iberm, Iowbs, Tfesc).IP, Switchgr.SG/

 L Categories of land
   /Cropland, Cropast, Pastran, CRP/

 LC(L) Crop land
   /Cropland, Cropast, CRP/

 LK(L,K) Mapping biomass types to suitable land in which they can be grown
   /(Cropland, Cropast, CRP).(Wheatstr, Cornstov, Cowbs, CNamixed, Iberm,
     Iowbs, Tfesc, Switchgr), Pastran.(Natall, Namixed, Nashort)/

 BC Biomass production cost categories
   /Estcost, Maincost, Landrent, Biopcost/

 BCO(BC) Biomass opportunity cost categories
   /Landrent, Biopcost/

 G Products and by-products of the process
   /Ethanol, CO2, N2, Ash/

 E(G) Ethanol only
   /Ethanol/

 B(G) Process by-products
   /CO2, N2, Ash/

 S Plant Size
   /Small, Medium, Large/

 FT Facility type at the plant location
  /Storage, Process/

 M Months of the production year
   /Mar, Apr, May, Jun, Jul, Aug, Sep, Oct, Nov, Dec, Jan, Feb/

 M1(M) The first month of the production year
   /Mar/

 M2(M) Months after the first month
   /Apr, May, Jun, Jul, Aug, Sep, Oct, Nov, Dec, Jan, Feb/

**********************************************************************
**Energy consuming machinery-intensive activities/sets follow        *
**********************************************************************

 AMI All machinery-intensive activities
   /Tillage, Planting, Cutting, Raking, Baling, Transprt, Grinding/

 FA(AMI) Field activities
   /Tillage, Planting, Cutting, Raking, Baling/
```

```
 TF Type of field activities
   /Estab, Harvest/

 TFA(TF,FA) Mapping field activity category to the activities
   /Estab.(Tillage, Planting), Harvest.(Cutting, Raking, Baling)/

SCALAR BIPROP Proportion of biomass acres available for biorefinery /0.10/;

SCALAR CBIPROP Proportion of CRP biomass acres available for biorefinery /0.25/;

SCALAR DR "Discount rate" /0.15/;

SCALAR T "Project life in years" /15/;

********************************************************************
**CO2 yield: For every 1 gallon of ethanol produced, 6.33 lbs      *
**of CO2 are formed (assuming fermentation process):               *
**Solar Energy Information Data Bank. "Fuel From Farms: A Guide    *
**  to Small-Scale Ethanol Production." Solar Energy Research      *
**  Institute, Operated for the U.S. Dept of Energy (Midwest       *
**  Research Institute), February 1980.                            *
**However, zero-carbon balance is assumed here (IOC = 0)           *
********************************************************************

SCALAR
  IOE Transformation rate in gallons of ethanol per ton of biomass  /60/
  IOC Transformation rate in tons of CO2 per ton of biomass  /0/
  ION Transformation rate in tons of N per ton of biomass  /0/
  IOA Trans rate in tons of ash and other byproducts per ton of biomass /0/;

PARAMETER LAMBDA(K,G) Input-output coefficients;
  LAMBDA(K,G)$(ORD(G) EQ 1) = IOE;
  LAMBDA(K,G)$(ORD(G) EQ 2) = IOC;
  LAMBDA(K,G)$(ORD(G) EQ 3) = ION;
  LAMBDA(K,G)$(ORD(G) EQ 4) = IOA;

**********************************************************************
**The following estimates of diesel energy content (DBTU), gasoline  *
**energy content (GBTU) and energy expended to produce a lb of       *
**nitrogen (NBTU) were obtained from:                                *
**Shapouri, H., J.A. Duffield and M.S. Graboski. "Estimating the     *
**    Energy Balance of Corn Ethanol." U.S. Dept. of Agriculture,    *
**    Economic Research Service, Office of Energy, Agricultural      *
**    Economic Report No. 721, Washington, DC, July 1995.            *
**********************************************************************

SCALAR DBTU "Energy (Btu) contained in a gallon of diesel" /137202/;

SCALAR GBTU "Energy (Btu) contained in a gallon of gasoline" /125073/;

SCALAR NBTU "Energy (Btu) spent to produce a lb of nitrogen" /22159/;

**********************************************************************
**The following estimate of ethanol energy content (EBTU) was        *
**obtained from:                                                     *
**Hohman, N., and C.M. Rendleman. "Emerging Technologies in Ethanol  *
**     Production."  Agriculture Information Bulletin Number 663,    *
**     Economic Research Service, U.S. Dept of Agric., January 1993. *
**********************************************************************

SCALAR EBTU "Energy (Btu) contained in a gallon of ethanol" /78000/;

**********************************************************************
**The following fuel multiplier (FUMULT) was obtained from Huhnke    *
**********************************************************************

SCALAR FUMULT Fuel multiplier in gallons per horsepower hour /0.044/;

*********************************************************************
**The following MPG estimate is an average of the forecasts 1993 for*
```

```
**the period 1992-2000                                              *
**Source:                                                           *
**California Department of Transportation, Office of Traffic        *
**   Improvement. "California Motor Vehicle Stock, Travel and Fuel  *
**   Forecast."  U.S. Department of Transportation, Federal Highway *
**   Administration, November 1993. Available at                    *
**   http://www.bts.gov/ntl/DOCS/cal.html, June 26, 2000            *
*********************************************************************

SCALAR TRKLOAD Truck capacity in tons of biomass /17/;

SCALAR MPG "Diesel consumption rate/economy by 17 ton truck" /5.43/;

PARAMETER GPM Gallons of diesel per mile traveled;
  GPM = 1/MPG;

*********************************************************************
**The following GHP estimate was obtained by personal communication *
**grinder manufacturer (Huhnke, June 2000)                          *
*********************************************************************

SCALAR GHP  Grinding machinery horsepower hours per ton of biomass  /15/;

*********************************************************************
**The following horsepower estimates for field machinery were       *
**obtained from Huhnke                                              *
*********************************************************************

PARAMETER HPOWER(FA) Horse power for field and grinding machinery
   /Tillage 150, Planting 75, Cutting 75, Raking 75, Baling 150/;

PARAMETER FLDSPEED(FA) Speed for field machinery in acres per hour
   /Tillage 7.73, Planting 9.33, Cutting 6.65, Raking 10.47, Baling 20.36/;

SCALAR
   CRUDPRIC "Price of crude oil in $/barrel" /25/
   DIEPRI0  Initial price of diesel in dollars per gallon /0.80/
   ETHPRIC  Competetive price of ethanol /0.67/;

PARAMETER CRUDPRI0 Initial price of crude oil in dollars per barrel;
   CRUDPRI0 = (DIEPRI0-0.1526)/0.0242;

PARAMETER CDEPR "Competitive diesel-ethanol price ratio";
   CDEPR = (0.1526 + 0.0242*CRUDPRIC)/ETHPRIC;

PARAMETER FLDIES(FA) Diesel used in field activities in gallons per acre;
   FLDIES(FA) = FUMULT*HPOWER(FA)/FLDSPEED(FA);

PARAMETER GRDIES Diesel used to grind a ton of biomass in gallons;
   GRDIES = FUMULT*GHP;

**********************************************************************
**A factor of 0.5 is used to scale both storage and processing       *
**  facility capacities up/down to other plant sizes                 *
**********************************************************************

SCALAR CAPADJ "Capacity scaling/adjustment factor" /0.5/;

**********************************************************************
**Assume that doubling plant size will increase construction         *
**  costs by 70 % (Johannes, 2004)                                   *
**********************************************************************

SCALAR COADJ  "Construction cost scaling/adjustment factor" /1.7/;

*********************************************************************
**An annual processing capacity of 42,000,000 gallons of ethanol is *
**  assumed to be the medium plant size                             *
**Storage capacities indicated below (in tons of biomass) assume an *
**  equivalent of three weeks of the processing facility's annual   *
**  capacity (Huhnke, 2004)                                         *
```

```
*********************************************************************

PARAMETER CAP42(FT) "Processing/storage capacity for 42 m gal plant"
   /STORAGE     42000
    PROCESS  42000000 /;

PARAMETER CAP(S,FT) Storage and processing capacity by plant size;
   CAP(S,FT)$(ORD(S) EQ 2) = CAP42(FT);
   CAP(S,FT)$(ORD(S) EQ 1) = CAP42(FT)*CAPADJ;
   CAP(S,FT)$(ORD(S) EQ 3) = CAP42(FT)/CAPADJ;

PARAMETER CAPP(S) "Facility monthly capacity in gallons";
   CAPP(S) = CAP(S,"PROCESS")/12;

********************************************************************
**$100 million processing facility construction costs              *
**  is assumed for the 42 million gallon plant (Johannes, 2004)    *
**Construction of a corresponding storage facility is estimated    *
**  to cost about $1,528,846 (Huhnke, 2004)                        *
********************************************************************

PARAMETER FC42(FT) "Construction costs for 42 m gallon plant in $"
   /STORAGE   1528846
    PROCESS 100000000 /;

PARAMETER FC(S,FT) Construction and facility costs by plant size;
   FC(S,FT)$(ORD(S) EQ 2) = FC42(FT);
   FC(S,FT)$(ORD(S) EQ 1) = FC42(FT)/COADJ;
   FC(S,FT)$(ORD(S) EQ 3) = FC42(FT)*COADJ;

PARAMETER OMAP(FT) "Annual O & M costs as a proportion of total investment"
   /STORAGE 0.02
    PROCESS 0.05 /;

PARAMETER OMA(S, FT) "Total annual O & M costs in $ by plant size and facility";
   OMA(S,FT) = FC(S,FT)*OMAP(FT);

TABLE FSV(S,FT) "Facility salvage value in $ by plant size"
             Storage     Process
  Small         0            0
  Medium        0            0
  Large         0            0      ;

**The following formula amortizes the total facility fixed costs    *

PARAMETER AFC(S,FT) Facility annual fixed charge by plant size;
  AFC(S,FT)=[FC(S,FT)-FSV(S,FT)]*[DR*POWER{(1+DR),T}]/[POWER{(1+DR),T}-1];

PARAMETER TAFC(S,FT) Facility annual construction and operating costs by size;
  TAFC(S,FT) = AFC(S,FT) + OMA(S,FT);

PARAMETER PVAF Present worth of an annuity factor;
  PVAF= [POWER{(1+DR),T}-1]/[DR*POWER{(1+DR),T}];

PARAMETER BINV(S) Biomass minimum inventory at the plant
    /Small         0
     Medium        0
     Large         0    /;

********************************************************************
**CO2 and N2 cost data were obtained from:                         *
**Bernow, S. S., and D. B. Marron.  "Valuation of Environmental    *
**      Externalities for Energy Planning and Operations,          *
**      May 1990 Update."  Tellus Institute, Boston, MA, May 1990. *
**NOTE: Obtained by a revealed preference procedure.               *
*********************Updated to 1992 (Ag-West Biotech Inc).*********

PARAMETER RHO(G) "Output price vector in $ per unit"
  /Ethanol    1.25
   CO2      -24.70
   N2      -246.40
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   Ash       -0.02/;

PARAMETER DIEPRI Price of diesel given price of crude oil;
*   DIEPRI = CDEPR*RHO("Ethanol");
   DIEPRI = DIEPRI0;

PARAMETER CRUDPRI Price of crude oil in dollars per barrel;
   CRUDPRI = (DIEPRI-0.1526)/0.0242;

SCALAR PN "Price of nitrogen in $ per lb" /0.24/;

PARAMETER NIT(KF) Level of nitrogen by fertility program in lb per acre
   /Wheatst  0, Cornsto  0, Cowbst  0, Nmixed   0,
    Ntall  0, Nmixed   0, Nshort  0, Iberm50  50,
    Iberm100  100, Iberm150  150, Iberm200 200, Iowbs50 50,
    Iowbs100 100, Iowbs150 150, Iowbs200 200, Tfesc50 50,
    Tfesc100 100, Tfesc150 150, Tfesc200 200, Switchg  75 /;

PARAMETER NCOST(KF) Cost of applied nitrogen in USD per acre;
   NCOST(KF) = NIT(KF)*PN;

TABLE YAD(K,M) Proportion of potential yield by harvest month

         Mar  Apr  May  Jun  Jul  Aug  Sep  Oct  Nov  Dec  Jan  Feb
Wheatstr   0    0    0 1.00 1.00    0    0    0    0    0    0    0
Cornstov   0    0    0    0    0    0 1.00 1.00    0    0    0    0
Cowbs      0    0    0    0 1.00 1.00    0    0    0    0    0    0
CNamixed   0    0    0    0 1.00 1.00    0    0    0    0    0    0
Natall     0    0    0    0 1.00 1.00 1.00 0.95 0.90 0.85 0.80 0.75
Namixed    0    0    0    0 1.00 1.00 1.00 0.95 0.90 0.85 0.80 0.75
Nashort    0    0    0    0 1.00 1.00 1.00 0.95 0.90 0.85 0.80 0.75
Iberm      0    0    0    0 1.00 1.00 1.00 0.95 0.90 0.85 0.80 0.75
Iowbs      0    0    0    0 1.00 1.00 1.00 0.95 0.90 0.85 0.80 0.75
Tfesc      0    0    0 1.00 0.90 0.80 0.75    0    0    0    0    0
Switchgr   0    0    0    0 1.00 1.00 1.00 0.95 0.90 0.85 0.80 0.75
;

PARAMETER THETAI(K) Usable proportion of stored biomass at the source
    /Wheatstr  0.995
     Cornstov  0.995
     Cowbs     0.995
     CNamixed  0.995
     Natall    0.995
     Namixed   0.995
     Nashort   0.995
     Iberm     0.995
     Iowbs     0.995
     Tfesc     0.995
     Switchgr  0.995    /;

PARAMETER THETAJ(K) Usable proportion of stored biomass at the plant
    /Wheatstr  0.999
     Cornstov  0.999
     Cowbs     0.999
     CNamixed  0.999
     Natall    0.999
     Namixed   0.999
     Nashort   0.999
     Iberm     0.999
     Iowbs     0.999
     Tfesc     0.999
     Switchgr  0.999    /;

PARAMETER GAMMA(K) Biomass storage cost at source in USD per ton (Huhnke 2004)
    /Wheatstr  2.00
     Cornstov  2.00
     Cowbs     2.00
     CNamixed  2.00
     Natall    2.00
     Namixed   2.00
     Nashort   2.00
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     Iberm     2.00
     Iowbs     2.00
     Tfesc     2.00
     Switchgr  2.00    /;

PARAMETER PSI(K) Biomass purchase cost in USD per ton
    /Wheatstr  10.00
     Cornstov  10.00
     Cowbs         0
     CNamixed      0
     Natall    10.00
     Namixed   10.00
     Nashort   10.00
     Iberm     10.00
     Iowbs     10.00
     Tfesc     10.00
     Switchgr  10.00    /;

********************************************************************
**The cost of applying fertilizer is assumed to be constant at     *
**$3/acre as long as some fertilizer is applied (Epplin, 2004).    *
**In the next table, this cost is presented as maintenance cost,   *
**"Maincost".                                                      *
********************************************************************

TABLE POC(K,BC) "Biomass production and opportunity costs in $ per acre"
               Estcost   Maincost   Landrent   Biopcost
  Wheatstr         0          0         0          0
  Cornstov         0          0         0          0
  Cowbs            0       3.00     10.00          0
  CNamixed         0          0     10.00          0
  Natall           0          0         0          0
  Namixed          0          0         0          0
  Nashort          0          0         0          0
  Iberm            0       3.00         0          0
  Iowbs            0       3.00         0          0
  Tfesc            0       3.00         0          0
  Switchgr     11.22       3.00         0          0        ;

PARAMETER TPOC(K) "Total production/procurement cost of feedstocks in $/acre";
  TPOC(K) = SUM(BC, POC(K,BC));

TABLE CURACRE(I,K) Current acreage for each biomass type not on CRP land
          Wheatstr  Cornstov   Natall   Namixed
Adair         620        0     73483      3868
Alfalfa    226000      540     12442     93317
Atoka         460        0    151207     16801
Beaver     102000     7700         0         0
Beckham     48000        0    112352    140440
Blaine     132000      220     20861    156460
Bryan        6300     2660    179386     19932
Caddo      144000     3400    109328    136661
Canadian   146000      420     17113    128351
Carter       1440       60     89987    112484
Cherokee      240        0     60717      3196
Choctaw      1190     2460    133281     14809
Cimarron   101000    32000         0         0
Clevelan     5900      520     23713     29641
Coal          260        0    120864     13429
Comanche    49400     4600     90512    113140
Cotton      71000      740     53349     66687
Craig        9800     2280    238289     12542
Creek        2140        0    146123      7691
Custer     156000      840     29891    224186
Delaware     2400        0     88760      4672
Dewey      109000      460     35653    267398
Ellis       46000     3420     47867    359003
Garfield   276000     1280     16753    125648
Garvin       5500     2420     96882    121102
Grady       51200     3360    117680    147100
Grant      306000     1380     14226    106697
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Greer       73000        0     56485     70607
Harmon      32600      360     52743     65929
Harper      61000     1680     38988    292412
Haskell       820      960    108494     12055
Hughes       1540     1460    154688     17188
Jackson    139000       80     54259     67824
Jeffers     10600        0    103424    129280
Johnston     1260        0    165169     18352
Kay        180000     5700    128268      6751
Kingfish   175000      400     15737    118029
Kiowa      201000      720     91918    114898
LeFlore      5000     2720    116160     12907
Lincoln      2800      540    187546      9871
Logan       57600      240     14704    110278
Love         4140        0     46014     57518
Major       97000     2460     21832    163738
Marshall     1380      380     85658      9518
Mayes        5600     1160    101373      5335
McClain      9000     1380     59088     73861
McCurt       2700     8820    109243     12138
McIntosh      700      220    100694     11188
Murray       1020       80    113558     12618
Muskogee     7400     6380    133077      7004
Noble      125000      680    163210      8590
Nowata       3400     1200    185271      9751
Okfuskee     1300      780    131491      6921
Oklahoma    12900      840      6254     46907
Okmulgee     3700     2040    127830      6728
Osage       15000        0    868794     45726
Ottawa      24400     3560     71080      3741
Pawnee       7900        0    165380      8704
Payne       12600      440    156088      8215
Pittsbur      580      300    191315     21257
Pontotoc      640        0    159267     17696
Pottawat     8500     1620    123182     13687
RogerMil    36000        0     54313    407345
Rogers       8400      100    136555      7187
Seminole     1060        0    104144     11572
Sequoyah     2400     5300     69543      7727
Stephens    10000       60     87865    109831
Texas      180000    80200         0         0
Tillman    118000     9020     56727     70909
Tulsa        2200        0     49591      2610
Wagoner     14100     3780     87735      4618
Washing      7800      300    123630      6507
Washita    180000       80     77870     97338
Woods      164000        0     48700    365252
Woodward    70000        0     50676    380072

+        Nashort    Iberm    Iowbs    Tfesc    Switchgr
Adair          0    22382      448    18800          0
Alfalfa    18663    18484    16485      500          0
Atoka          0    71145      988    19763          0
Beaver    597626        0    60307     5946          0
Beckham    28088    34812    19430      810          0
Blaine     31292    31097    27736      840          0
Bryan          0    72416     1006    20116          0
Caddo      27332    53529    29877     1245          0
Canadian   25670    34567    30830      934          0
Carter     22497    44664    24929     1039          0
Cherokee       0    24278      486    20394          0
Choctaw        0    48028      667    13341          0
Cimarron  624654        0    57076     5627          0
Clevelan    5928    15907     8878      370          0
Coal           0    38578      536    10716          0
Comanche   22628    30636    17099      712          0
Cotton     13337    32862    18342      764          0
Craig          0    26633      533    22371          0
Creek          0    33819      676    28408          0
Custer     44837    28900    25776      781          0
Delaware       0    27623      552    23203          0
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Dewey      53480    22226    19823      601          0
Ellis      71801    20966    18699      567          0
Garfield   25130    28605    25512      773          0
Garvin     24220    38728    21616      901          0
Grady      29420    43058    24033     1001          0
Grant      21339    17209    15348      465          0
Greer      14121    20736    11574      482          0
Harmon     13186    20627    11513      480          0
Harper     58482    19370    17276      524          0
Haskell        0    39841      553    11067          0
Hughes         0    51048      709    14180          0
Jackson    13565    22233    12409      517          0
Jeffers    25856    34841    19446      810          0
Johnston       0    42808      595    11891          0
Kay            0    20566      411    17275          0
Kingfish   23606    41699    37191     1127          0
Kiowa      22980    34178    19076      795          0
LeFlore        0    60882      846    16912          0
Lincoln        0    52672     1053    44244          0
Logan      22056    28072    25037      759          0
Love       11504    22199    12390      516          0
Major      32748    26937    24025      728          0
Marshall       0    16548      230     4597          0
Mayes          0    28276      566    23752          0
McClain    14772    26938    15035      626          0
McCurt         0    52971      736    14714          0
McIntosh       0    37191      517    10331          0
Murray         0    21116      293     5866          0
Muskogee       0    30336      607    25482          0
Noble          0    21938      439    18428          0
Nowata         0    20770      415    17446          0
Okfuskee       0    28163      563    23657          0
Oklahoma    9381    10883     9706      294          0
Okmulgee       0    24586      492    20652          0
Osage          0    45310      906    38060          0
Ottawa         0    15216      304    12781          0
Pawnee         0    17718      354    14883          0
Payne          0    35092      702    29477          0
Pittsbur       0    62898      874    17472          0
Pontotoc       0    62227      864    17285          0
Pottawat       0    48972      680    13603          0
RogerMil   81469    34810    31047      941          0
Rogers         0    26844      537    22549          0
Seminole       0    49697      690    13805          0
Sequoyah       0    31676      440     8799          0
Stephens   21966    42963    23979      999          0
Texas     453574        0    36302     3579          0
Tillman    14182    29890    16683      695          0
Tulsa          0    14605      292    12268          0
Wagoner        0    14560      291    12230          0
Washing        0    11753      235     9872          0
Washita    19468    40345    22518      938          0
Woods      73050    25433    22683      687          0
Woodward   76014    28747    25639      777          0
;

TABLE CCURACRE(I,K) Current acreage for each biomass type on CRP Land
                 Cowbs           CNamixed
Adair               0                  0
Alfalfa          8344               4493
Atoka               0                  0
Beaver          88031              47401
Beckham         32346              17417
Blaine           4633               2495
Bryan            2657               1431
Caddo            5002               2693
Canadian         1152                620
Carter            163                 88
Cherokee            0                  0
Choctaw             0                  0
Cimarron       159781                  0
```

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Clevelan             0                  0
Coal                47                 26
Comanche           470                253
Cotton            3244               1747
Craig              434                234
Creek                0                  0
Custer            3277               1765
Delaware            32                 17
Dewey            11753               6328
Ellis            41673              22440
Garfield          4002               2155
Garvin              30                 16
Grady             1464                789
Grant            15202               8185
Greer            22534              12133
Harmon           33756              18176
Harper           40787              21962
Haskell            297                160
Hughes             120                 64
Jackson          14007               7542
Jeffers           5123               2759
Johnston             0                  0
Kay               2662               1433
Kingfish          3613               1946
Kiowa             5405               2911
LeFlore              0                  0
Lincoln            378                203
Logan             1618                871
Love               463                250
Major            12276               6610
Marshall           226                121
Mayes                0                  0
McClain             47                 26
McCurt             692                373
McIntosh             0                  0
Murray               0                  0
Muskogee            86                 46
Noble             1234                664
Nowata             117                 63
Okfuskee           230                124
Oklahoma             0                  0
Okmulgee           308                166
Osage              651                351
Ottawa             180                 97
Pawnee               0                  0
Payne              172                 93
Pittsbur             0                  0
Pontotoc            42                 22
Pottawat           261                140
RogerMil         14723               7928
Rogers              35                 19
Sequoyah             0                  0
Seminole           150                 81
Stephens           974                525
Texas           131270              87513
Tillman           7450               4011
Tulsa               23                 12
Wagoner            114                 61
Washing              0                  0
Washita           3552               1912
Woods            17774               9570
Woodward         13101               7054
;

TABLE POTACRES(I,L) Potential acres by land category
          Cropland        Cropast        Pastran        CRP
Adair        46324          44763          77351          0
Alfalfa     271955          49956         124422      12837
Atoka        57748          98813         168008          0
Beaver      310308          84939         597626     135432
Beckham     157723          80958         280879      49763
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Blaine      219363          84047         208613       7128
Bryan        97369         100578         199318       4088
Caddo       260929         124486         273321       7695
Canadian    214127          93425         171134       1772
Carter       45923         103869         224967        250
Cherokee     43416          48556          63913          0
Choctaw      60391          66705         148090          0
Cimarron    388657          80389         624654     159781
Clevelan     40745          36992          59282          0
Coal         35403          53581         134293         73
Comanche    106891          71247         226280        723
Cotton      118662          76423         133373       4990
Craig       100880          53265         250831        668
Creek        63439          67638         153814          0
Custer      206020          78109         298914       5042
Delaware     68807          55246          93432         49
Dewey       144416          60071         356531      18081
Ellis       126125          56664         478670      64113
Garfield    370406          77310         167530       6157
Garvin       90184          90066         242204         46
Grady       166458         100136         294200       2253
Grant       390519          46510         142263      23387
Greer       127020          48223         141213      34667
Harmon      109729          47969         131858      51932
Harper      152270          52350         389883      62749
Haskell      53092          55335         120549        457
Hughes       54102          70900         171875        184
Jackson     257345          51705         135648      21549
Jeffers      46183          81025         258559       7882
Johnston     36826          59455         183521          0
Kay         282574          41131         135019       4095
Kingfish    259205         112701         157372       5559
Kiowa       261360          79483         229795       8316
LeFlore     100105          84559         129067          0
Lincoln      88540         105343         197417        581
Logan       102716          75870         147037       2489
Love         42413          51625         115035        713
Major       181718          72804         218317      18886
Marshall     22672          22983          95175        347
Mayes        94805          56552         106708          0
McClain      70625          62646         147721         73
McCurt       72282          73571         121381       1065
McIntosh     54492          51654         111882          0
Murray       24577          29328         126175          0
Muskogee    110552          60671         140081        132
Noble       162132          43876         171800       1898
Nowata       53785          41539         195022        180
Okfuskee     39840          56325         138412        354
Oklahoma     55254          29413          62543          0
Okmulgee     64530          49171         134558        474
Osage        79304          90619         914520       1002
Ottawa       94520          30432          74821        277
Pawnee       45139          35435         174084          0
Payne        66127          70184         164303        265
Pittsbur     72631          87358         212572          0
Pontotoc     56046          86426         176963         64
Pottawat     77077          68016         136869        401
RogerMil     87505          94081         543126      22651
Rogers       78678          53688         143742         54
Sequoyah     58952          43994          77270          0
Seminole     48128          69024         115715        230
Stephens     60311          99913         219662       1499
Texas       524360          51130         453574     218783
Tillman     262696          69512         141818      11461
Tulsa        51560          29209          52201         35
Wagoner     102480          29119          92353        175
Washing      51866          23505         130137          0
Washita     266911          93825         194676       5464
Woods       246998          68737         487003      27344
Woodward    128111          77695         506762      20155
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TABLE BIOYLD1(I,KF) Biomass yield in lbs per acre
            Wheatst        Cornsto       Cowbst     CNmixed
Adair         3554              0            0           0
Alfalfa       3909           7027         3513        3513
Atoka         2946              0            0           0
Beaver        2873           7803         2459        2459
Beckham       3030              0         3513        3513
Blaine        3329           4770         3513        3513
Bryan         3432           5639         7729        7729
Caddo         3811           6067         3513        3513
Canadian      3694           5498         3513        3513
Carter        2937           3878         6323        6323
Cherokee      3288              0            0           0
Choctaw       3197           6383            0           0
Cimarron      3266           7662         2459        2459
Clevelan      3395           5752            0           0
Coal          3086              0         6323        6323
Comanche      3133           5301         4918        4918
Cotton        3180           4950         4918        4918
Craig         3772           5512         7729        7729
Creek         3660              0            0           0
Custer        3647           5860         3513        3513
Delaware      4002              0         7729        7729
Dewey         3384           4960         3513        3513
Ellis         2823           7658         3513        3513
Garfield      3666           6311         4918        4918
Garvin        3853           6529         4918        4918
Grady         3578           6263         4918        4918
Grant         3619           6073         4918        4918
Greer         2924              0         3513        3513
Harmon        2924           4632         3513        3513
Harper        3010           7666         3513        3513
Haskell       3068           6308         7729        7729
Hughes        3769           6085         6323        6323
Jackson       3180           3735         3513        3513
Jeffers       3337              0         6323        6323
Johnston      3068              0            0           0
Kay           3535           6129         6323        6323
Kingfish      3619           5541         3513        3513
Kiowa         3268           4209         3513        3513
LeFlore       3458           5852            0           0
Lincoln       3731           5880         6323        6323
Logan         3460           4334         4918        4918
Love          3423              0         6323        6323
Major         3279           7725         3513        3513
Marshall      3189           4919         6323        6323
Mayes         3740           5445            0           0
McClain       3376           6052         4918        4918
McCurt        3582           5709         8431        8431
McIntosh      3862           4429            0           0
Murray        3114           3807            0           0
Muskogee      3853           6913         7729        7729
Noble         3441           5135         4918        4918
Nowata        3264           5599         7729        7729
Okfuskee      3040           5861         6323        6323
Oklahoma      3284           5872            0           0
Okmulgee      3998           6000         6323        6323
Osage         3402              0         6323        6323
Ottawa        3972           5848         7729        7729
Pawnee        3466              0            0           0
Payne         3331           5686         6323        6323
Pittsbur      3750           4671            0           0
Pontotoc      3430              0         6323        6323
Pottawat      3591           6246         4918        4918
RogerMil      3107              0         3513        3513
Rogers        3320           3684         7729        7729
Seminole      3124              0         6323        6323
Sequoyah      3957           6660            0           0
Stephens      3213           3935         4918        4918
Texas         3918           8089         2459        2459
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Tillman       3213           5067         3513        3513
Tulsa         3638              0         7729        7729
Wagoner       3955           5824         7729        7729
Washing       3703           4499            0           0
Washita       3413           3678         3513        3513
Woods         3658              0         3513        3513
Woodward      3346              0         3513        3513

+         Ntall    Nmixed   Nshort   Iberm50  Iberm100 Iberm150
Adair      6000     3800         0     3500     4660     6000
Alfalfa    3140     2540      1900     3480     5000     6000
Atoka      4180     3360         0     4080     7000     9000
Beaver        0        0      1340        0        0        0
Beckham    2800     2500      1700     4540     6000     7500
Blaine     3140     2540      1900     3480     5000     6000
Bryan      4180     3360         0     4080     7000     9000
Caddo      2800     2500      1700     4540     6000     7500
Canadian   3140     2540      1900     3480     5000     6000
Carter     2800     2500      1700     4540     6000     7500
Cherokee   6000     3800         0     3500     4660     6000
Choctaw    4180     3360         0     4080     7000     9000
Cimarron      0        0      1340        0        0        0
Clevelan   2800     2500      1700     4540     6000     7500
Coal       4180     3360         0     4080     7000     9000
Comanche   2800     2500      1700     4540     6000     7500
Cotton     2800     2500      1700     4540     6000     7500
Craig      6000     3800         0     3500     4660     6000
Creek      6000     3800         0     3500     4660     6000
Custer     3140     2540      1900     3480     5000     6000
Delaware   6000     3800         0     3500     4660     6000
Dewey      3140     2540      1900     3480     5000     6000
Ellis      3140     2540      1900     3480     5000     6000
Garfield   3140     2540      1900     3480     5000     6000
Garvin     2800     2500      1700     4540     6000     7500
Grady      2800     2500      1700     4540     6000     7500
Grant      3140     2540      1900     3480     5000     6000
Greer      2800     2500      1700     4540     6000     7500
Harmon     2800     2500      1700     4540     6000     7500
Harper     3140     2540      1900     3480     5000     6000
Haskell    4180     3360         0     4080     7000     9000
Hughes     4180     3360         0     4080     7000     9000
Jackson    2800     2500      1700     4540     6000     7500
Jeffers    2800     2500      1700     4540     6000     7500
Johnston   4180     3360         0     4080     7000     9000
Kay        6000     3800         0     3500     4660     6000
Kingfish   3140     2540      1900     3480     5000     6000
Kiowa      2800     2500      1700     4540     6000     7500
LeFlore    4180     3360         0     4080     7000     9000
Lincoln    6000     3800         0     3500     4660     6000
Logan      3140     2540      1900     3480     5000     6000
Love       2800     2500      1700     4540     6000     7500
Major      3140     2540      1900     3480     5000     6000
Marshall   4180     3360         0     4080     7000     9000
Mayes      6000     3800         0     3500     4660     6000
McClain    2800     2500      1700     4540     6000     7500
McCurt     4180     3360         0     4080     7000     9000
McIntosh   4180     3360         0     4080     7000     9000
Murray     4180     3360         0     4080     7000     9000
Muskogee   6000     3800         0     3500     4660     6000
Noble      6000     3800         0     3500     4660     6000
Nowata     6000     3800         0     3500     4660     6000
Okfuskee   6000     3800         0     3500     4660     6000
Oklahoma   3140     2540      1900     3480     5000     6000
Okmulgee   6000     3800         0     3500     4660     6000
Osage      6000     3800         0     3500     4660     6000
Ottawa     6000     3800         0     3500     4660     6000
Pawnee     6000     3800         0     3500     4660     6000
Payne      6000     3800         0     3500     4660     6000
Pittsbur   4180     3360         0     4080     7000     9000
Pontotoc   4180     3360         0     4080     7000     9000
Pottawat   4180     3360         0     4080     7000     9000
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RogerMil   3140     2540      1900     3480     5000     6000
Rogers     6000     3800         0     3500     4660     6000
Seminole   4180     3360         0     4080     7000     9000
Sequoyah   4180     3360         0     4080     7000     9000
Stephens   2800     2500      1700     4540     6000     7500
Texas         0        0      1340        0        0        0
Tillman    2800     2500      1700     4540     6000     7500
Tulsa      6000     3800         0     3500     4660     6000
Wagoner    6000     3800         0     3500     4660     6000
Washing    6000     3800         0     3500     4660     6000
Washita    4180     3360         0     4080     7000     9000
Woods      3140     2540      1900     3480     5000     6000
Woodward   3140     2540      1900     3480     5000     6000

+          Iberm200  Iowbs50  Iowbs100  Iowbs150  Iowbs200
Adair        8500      2500     4620      5500      6500
Alfalfa      9000      2660     4040      5000      6000
Atoka       11000      3000     4720      5500      7000
Beaver          0      2660     4000      5000      6000
Beckham      8500      3000     4620      6000      7500
Blaine       9000      2660     4040      5000      6000
Bryan       11000      3000     4721      5500      7000
Caddo        8500      3000     4620      6000      7500
Canadian     9000      2660     4040      5000      6000
Carter       8500      3000     4620      6000      7500
Cherokee     8500      2500     4620      5500      6500
Choctaw     11000      3000     4722      5500      7000
Cimarron        0      2660     4000      5000      6000
Clevelan     8500      3000     4620      6000      7500
Coal        11000      3000     4723      5500      7000
Comanche     8500      3000     4620      6000      7500
Cotton       8500      3000     4620      6000      7500
Craig        8500      2500     4620      5500      6500
Creek        8500      2500     4620      5500      6500
Custer       9000      2660     4040      5000      6000
Delaware     8500      2500     4620      5500      6500
Dewey        9000      2660     4040      5000      6000
Ellis        9000      2660     4040      5000      6000
Garfield     9000      2660     4040      5000      6000
Garvin       8500      3000     4620      6000      7500
Grady        8500      3000     4620      6000      7500
Grant        9000      2660     4040      5000      6000
Greer        8500      3000     4620      6000      7500
Harmon       8500      3000     4620      6000      7500
Harper       9000      2660     4040      5000      6000
Haskell     11000      3000     4724      5500      7000
Hughes      11000      3000     4725      5500      7000
Jackson      8500      3000     4620      6000      7500
Jeffers      8500      3000     4620      6000      7500
Johnston    11000      3000     4726      5500      7000
Kay          8500      2500     4620      5500      6500
Kingfish     9000      2660     4040      5000      6000
Kiowa        8500      3000     4620      6000      7500
LeFlore     11000      3000     4727      5500      7000
Lincoln      8500      2500     4620      5500      6500
Logan        9000      2660     4040      5000      6000
Love         8500      3000     4620      6000      7500
Major        9000      2660     4040      5000      6000
Marshall    11000      3000     4728      5500      7000
Mayes        8500      2500     4620      5500      6500
McClain      8500      3000     4620      6000      7500
McCurt      11000      3000     4729      5500      7000
McIntosh    11000      3000     4730      5500      7000
Murray      11000      3000     4731      5500      7000
Muskogee     8500      2500     4620      5500      6500
Noble        8500      2500     4620      5500      6500
Nowata       8500      2500     4620      5500      6500
Okfuskee     8500      2500     4620      5500      6500
Oklahoma     9000      2660     4040      5000      6000
Okmulgee     8500      2500     4620      5500      6500
Osage        8500      2500     4620      5500      6500
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Ottawa       8500      2500     4620      5500      6500
Pawnee       8500      2500     4620      5500      6500
Payne        8500      2500     4620      5500      6500
Pittsbur    11000      3000     4732      5500      7000
Pontotoc    11000      3000     4733      5500      7000
Pottawat    11000      3000     4734      5500      7000
RogerMil     9000      2660     4040      5000      6000
Rogers       8500      2500     4620      5500      6500
Seminole    11000      3000     4735      5500      7000
Sequoyah    11000      3000     4736      5500      7000
Stephens     8500      3000     4620      6000      7500
Texas           0      2660     4000      5000      6000
Tillman      8500      3000     4620      6000      7500
Tulsa        8500      2500     4620      5500      6500
Wagoner      8500      2500     4620      5500      6500
Washing      8500      2500     4620      5500      6500
Washita     11000      3000     4737      5500      7000
Woods        9000      2660     4040      5000      6000
Woodward     9000      2660     4040      5000      6000

+          Tfesc50 Tfesc100  Tfesc150  Tfesc200  Switchg
Adair       4080     6000      7500      9500      13000
Alfalfa        0        0         0         0      10000
Atoka       3780     4500      6000      7500      13000
Beaver         0        0         0         0          0
Beckham        0        0         0         0          0
Blaine         0        0         0         0      10000
Bryan       3780     4500      6000      7500      12000
Caddo          0        0         0         0      12000
Canadian       0        0         0         0      10000
Carter         0        0         0         0      12000
Cherokee    4080     6000      7500      9500      13000
Choctaw     3780     4500      6000      7500      12000
Cimarron       0        0         0         0          0
Clevelan       0        0         0         0      10000
Coal        3780     4500      6000      7500      12000
Comanche       0        0         0         0          0
Cotton         0        0         0         0          0
Craig       4080     6000      7500      9500      12000
Creek       4080     6000      7500      9500      12000
Custer         0        0         0         0          0
Delaware    4080     6000      7500      9500      13000
Dewey          0        0         0         0          0
Ellis          0        0         0         0          0
Garfield       0        0         0         0      10000
Garvin         0        0         0         0      10000
Grady          0        0         0         0      10000
Grant          0        0         0         0      10000
Greer          0        0         0         0          0
Harmon         0        0         0         0          0
Harper         0        0         0         0          0
Haskell     3780     4500      6000      7500      13000
Hughes      3780     4500      6000      7500      13000
Jackson        0        0         0         0          0
Jeffers        0        0         0         0      10000
Johnston    3780     4500      6000      7500      12000
Kay         4080     6000      7500      9500      10000
Kingfish       0        0         0         0      10000
Kiowa          0        0         0         0          0
LeFlore     3780     4500      6000      7500      13000
Lincoln     4080     6000      7500      9500      12000
Logan          0        0         0         0      10000
Love           0        0         0         0      12000
Major          0        0         0         0          0
Marshall    3780     4500      6000      7500      12000
Mayes       4080     6000      7500      9500      12000
McClain        0        0         0         0      10000
McCurt      3780     4500      6000      7500      13000
McIntosh    3780     4500      6000      7500      13000
Murray      3780     4500      6000      7500      12000
Muskogee    4080     6000      7500      9500      12000
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Noble       4080     6000      7500      9500      10000
Nowata      4080     6000      7500      9500      12000
Okfuskee    4080     6000      7500      9500      12000
Oklahoma       0        0         0         0      12000
Okmulgee    4080     6000      7500      9500      12000
Osage       4080     6000      7500      9500      12000
Ottawa      4080     6000      7500      9500      12000
Pawnee      4080     6000      7500      9500      10000
Payne       4080     6000      7500      9500      10000
Pittsbur    3780     4500      6000      7500      13000
Pontotoc    3780     4500      6000      7500      12000
Pottawat    3780     4500      6000      7500      10000
RogerMil       0        0         0         0          0
Rogers      4080     6000      7500      9500      12000
Seminole    3780     4500      6000      7500      12000
Sequoyah    3780     4500      6000      7500      13000
Stephens       0        0         0         0      12000
Texas          0        0         0         0          0
Tillman        0        0         0         0          0
Tulsa       4080     6000      7500      9500      12000
Wagoner     4080     6000      7500      9500      12000
Washing     4080     6000      7500      9500      12000
Washita     3780     4500      6000      7500          0
Woods          0        0         0         0          0
Woodward       0        0         0         0          0
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*******************************************************************
**50 percent of each herbaceous biomass type is available for     *
**ethanol production in each biomass supplying county             *
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TABLE DELTA(I,J) Miles from biomass source i to facility location j
         Pontotoc  Jackson  Washing Canadian Garfield   Texas
Adair        199      346      161      240      239      450
Alfalfa      248      210      177      143       83      221
Atoka         80      314      210      189      245      427
Beaver       352      253      323      243      216      113
Beckham      230       93      310      138      190      227
Blaine       185      152      221       76       98      230
Bryan         96      237      262      205      261      443
Caddo        142      134      251       91      153      300
Canadian     144      163      206       33       95      273
Carter        95      188      256      157      213      394
Cherokee     180      327      136      215      213      425
Choctaw      132      294      241      241      297      479
Cimarron     460      361      444      351      324      111
Clevelan      93      161      195       74      130      311
Coal          58      229      198       99      223      405
Comanche     148       91      271      115      177      327
Cotton       143      103      282      127      189      341
Craig        209      334       79      218      208      412
Creek        118      244      109      127      146      354
Custer       208      113      265       99      142      234
Delaware     230      356      116      239      229      441
Dewey        232      142      244      123      115      198
Ellis        278      159      290      169      160      171
Garfield     200      215      165       95       33      245
Garvin        66      169      221      116      171      353
Grady        121      136      230       74      135      311
Grant        223      247      145      128       66      255
Greer        218       53      323      154      206      253
Harmon       236       64      352      186      238      276
Harper       293      203      254      184      156      148
Haskell       74      296      161      201      235      439
Hughes        66      225      162      131      186      369
Jackson      205       32      321      162      214      281
Jeffers      137      133      283      128      190      365
Johnston      66      208      230      169      225      406
Kay          200      274      122      155       94      282
Kingfish     158      176      190       54       68      254
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Kiowa       195      71       301      132      184      276
LeFlore     179      351      216      262      290      500
Lincoln     106      215      139       98      134      327
Logan       141      202      161       84       93      285
Love        103      194      264      165      221      403
Major       223      180      208      114       78      222
Marshall     75      201      239      169      225      407
Mayes       183      308       90      192      181      393
McClain      77      158      212       91      147      328
McCurt      184      346      293      294      349      531
McIntosh    135      281      141      176      213      414
Murray       63      183      224      144      200      382
Muskogee    156      303      125      191      199      410
Noble       162      232      133      116       72      283
Nowata      193      318       45      202      177      379
Okfuskee     95      235      141      130      178      367
Oklahoma    113      168      180       56      112      294
Okmulgee    114      260      108      155      174      383
Osage       196      321       75      205      155      357
Ottawa      227      352       98      236      226      432
Pawnee      153      265      110      149      101      312
Payne       137      234      129      117      97       299
Pittsbur    100      272      176      187      241      425
Pontotoc     29      202      193      140      196      378
Pottawat     81      200      168       96      152      334
RogerMil    256      118      309      151      185      207
Rogers      174      300       80      183      173      385
Seminole     70      222      162      128      183      365
Sequoyah    178      325      172      219      246      457
Stephens    120      121      262      106      168      344
Texas       398      298      383      289      261       49
Tillman     188       65      311      155      217      313
Tulsa       146      272       76      155      146      357
Wagoner     165      308      111      191      184      396
Washing     193      318       29      202      161      363
Washita     194       92      279      110      162      254
Woods       284      224      212      175      119      218
Woodward    256      166      246      147      120      157

+        Comanche Okmulgee   Payne  Woodward  Custer
Adair       294      125      185      326      283
Alfalfa     202      232      148      111      127
Atoka       185      127      185      302      231
Beaver      297      362      271      128      217
Beckham     150      267      217      128       94
Blaine      135      197      124      105       69
Bryan       180      157      201      318      247
Caddo        83      198      165      175       98
Canadian    115      164      119      148       77
Carter      132      183      180      270      198
Cherokee    275      100      160      300      258
Choctaw     236      158      236      354      283
Cimarron    406      470      380      236      325
Clevelan    109      138      109      187      116
Coal        172      115      163      280      209
Comanche     33      218      184      203      114
Cotton       48      229      196      216      128
Craig       283      128      155      292      261
Creek       192       67       86      229      170
Custer      134      228      169      109       55
Delaware    304      150      176      316      282
Dewey       163      243      152       74       84
Ellis       215      288      197       77      138
Garfield    177      183       99      121      133
Garvin      111      155      143      229      157
Grady        84      177      144      186      113
Grant       210      202      118      148      165
Greer       111      274      234      146      110
Harmon      120      299      265      177      142
Harper      238      303      212       69      158
Haskell     244       94      181      314      243
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Hughes      174       88      126      244      173
Jackson      90      268      235      166      118
Jeffers      79      225      197      241      159
Johnston    150      156      171      282      210
Kay         223      179       95      176      192
Kingfish    135      166       94      130       94
Kiowa       102      251      211      151       88
LeFlore     294      154      237      375      304
Lincoln     163       98       70      203      141
Logan       150      137       65      160      124
Love        139      192      189      278      207
Major       172      220      130       97       98
Marshall    144      165      176      282      210
Mayes       256      102      128      268      234
McClain     106      147      126      204      133
McCurt      289      211      289      407      336
McIntosh    230       66      155      289      218
Murray      126      151      148      257      185
Muskogee    251       76      145      286      233
Noble       181      144       56      159      157
Nowata      266      112      137      259      244
Okfuskee    183       65      117      243      172
Oklahoma    116      133       94      169       98
Okmulgee    209       24      115      258      197
Osage       269      143      125      237      247
Ottawa      300      146      172      312      278
Pawnee      214      124       64      188      190
Payne       182      122       31      175      158
Pittsbur    214       93      182      300      229
Pontotoc    144      119      135      253      182
Pottawat    149      105       91      209      138
RogerMil    175      280      213      113      107
Rogers      248       93      120      260      226
Seminole    171       91      123      241      170
Sequoyah    273      112      192      332      261
Stephens     63      209      175      219      142
Texas       343      408      317      174      263
Tillman      75      258      224      189      122
Tulsa       220       67       93      233      198
Wagoner     256       84      131      271      234
Washing     267      113      127      243      245
Washita     115      232      189      129       66
Woods       233      268      184      112      159
Woodward    202      266      176       32      121        ;

PARAMETER BYLD(I,KF) Biomass yield in tons per acre;
  BYLD(I,KF) = BIOYLD1(I,KF)/2000;

PARAMETER CURACRES(I,K) Available biomass in tons per acre;
  CURACRES(I,K) = BIPROP*CURACRE(I,K);

PARAMETER CCURACRES(I,K) Available biomass on CRP land in tons per acre;
  CCURACRES(I,K) = CBIPROP*CCURACRE(I,K);

PARAMETER TRCA(I,J)  "Biomass transportation cost in $ per 17 dry ton truck";
  TRCA(I,J) = 34.08 + [0.62*1.609+GPM*(DIEPRI-DIEPRI0)]*2*DELTA(I,J);

PARAMETER TAU(I,J)  "Biomass transportation cost in $ per ton";
  TAU(I,J) = TRCA(I,J)/TRKLOAD;

***********************************************************************************
** The following estimates of mean field-workdays in a particular month available *
** in Oklahoma were obtained from:                                                *
** Kletke, Darrel and Ross Sestak. "The Operation and Use of Machsel: A Farm      *
**    Machinery Selection Template." Computer Software Series CSS-53 September    *
**    1991, Agricultural Economics, Agricultural Experiment Station, Division of  *
**    Agriculture, Oklahoma State University.                                     *
** Reinschmiedt, Lynn L. "Study of the Relationship Between Rainfall and Fieldwork*
**    Time Available and its Effects on the Optimal Machinery Selection." MS      *
**    Thesis, Oklahoma State University, 1973.                                    *
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TABLE FWD(I,M) Field-Workdays Available in Oklahoma by county and month
                Mar     Apr     May     Jun     Jul     Aug     Sep
Adair           14.25   11.00   10.25   11.25   18.75   18.00   13.75
Alfalfa         19.00   13.25    9.25   12.50   16.00   19.25   16.13
Atoka           19.00   13.25    9.25   12.50   16.00   19.25   16.13
Beaver          21.25   21.50   18.00   17.50   17.00   18.50   19.00
Beckham         19.75   15.88   10.75   15.00   19.13   18.50   14.38
Blaine          19.75   15.88   10.75   15.00   19.13   18.50   14.38
Bryan           19.00   13.25    9.25   12.50   16.00   19.25   16.13
Caddo           19.75   15.88   10.75   15.00   19.13   18.50   14.38
Canadian        19.00   13.25    9.25   12.50   16.00   19.25   16.13
Carter          19.00   13.25    9.25   12.50   16.00   19.25   16.13
Cherokee        14.25   11.00   10.25   11.25   18.75   18.00   13.75
Choctaw         14.25   11.00   10.25   11.25   18.75   18.00   13.75
Cimarron        21.25   21.50   18.00   17.50   17.00   18.50   19.00
Clevelan        19.00   13.25    9.25   12.50   16.00   19.25   16.13
Coal            19.00   13.25    9.25   12.50   16.00   19.25   16.13
Comanche        19.75   15.88   10.75   15.00   19.13   18.50   14.38
Cotton          19.75   15.88   10.75   15.00   19.13   18.50   14.38
Craig           14.25   11.00   10.25   11.25   18.75   18.00   13.75
Creek           19.00   13.25    9.25   12.50   16.00   19.25   16.13
Custer          19.75   15.88   10.75   15.00   19.13   18.50   14.38
Delaware        14.25   11.00   10.25   11.25   18.75   18.00   13.75
Dewey           19.75   15.88   10.75   15.00   19.13   18.50   14.38
Ellis           19.75   15.88   10.75   15.00   19.13   18.50   14.38
Garfield        19.00   13.25    9.25   12.50   16.00   19.25   16.13
Garvin          19.00   13.25    9.25   12.50   16.00   19.25   16.13
Grady           19.00   13.25    9.25   12.50   16.00   19.25   16.13
Grant           19.00   13.25    9.25   12.50   16.00   19.25   16.13
Greer           19.75   15.88   10.75   15.00   19.13   18.50   14.38
Harmon          19.75   15.88   10.75   15.00   19.13   18.50   14.38
Harper          19.75   15.88   10.75   15.00   19.13   18.50   14.38
Haskell         14.25   11.00   10.25   11.25   18.75   18.00   13.75
Hughes          14.25   11.00   10.25   11.25   18.75   18.00   13.75
Jackson         19.75   15.88   10.75   15.00   19.13   18.50   14.38
Jeffers         19.00   13.25    9.25   12.50   16.00   19.25   16.13
Johnston        19.00   13.25    9.25   12.50   16.00   19.25   16.13
Kay             19.00   13.25    9.25   12.50   16.00   19.25   16.13
Kingfish        19.00   13.25    9.25   12.50   16.00   19.25   16.13
Kiowa           19.75   15.88   10.75   15.00   19.13   18.50   14.38
LeFlore         14.25   11.00   10.25   11.25   18.75   18.00   13.75
Lincoln         19.00   13.25    9.25   12.50   16.00   19.25   16.13
Logan           19.00   13.25    9.25   12.50   16.00   19.25   16.13
Love            19.00   13.25    9.25   12.50   16.00   19.25   16.13
Major           19.00   13.25    9.25   12.50   16.00   19.25   16.13
Marshall        19.00   13.25    9.25   12.50   16.00   19.25   16.13
Mayes           14.25   11.00   10.25   11.25   18.75   18.00   13.75
McClain         19.00   13.25    9.25   12.50   16.00   19.25   16.13
McCurt          14.25   11.00   10.25   11.25   18.75   18.00   13.75
McIntosh        14.25   11.00   10.25   11.25   18.75   18.00   13.75
Murray          19.00   13.25    9.25   12.50   16.00   19.25   16.13
Muskogee        14.25   11.00   10.25   11.25   18.75   18.00   13.75
Noble           19.00   13.25    9.25   12.50   16.00   19.25   16.13
Nowata          14.25   11.00   10.25   11.25   18.75   18.00   13.75
Okfuskee        19.00   13.25    9.25   12.50   16.00   19.25   16.13
Oklahoma        19.00   13.25    9.25   12.50   16.00   19.25   16.13
Okmulgee        14.25   11.00   10.25   11.25   18.75   18.00   13.75
Osage           14.25   11.00   10.25   11.25   18.75   18.00   13.75
Ottawa          14.25   11.00   10.25   11.25   18.75   18.00   13.75
Pawnee          14.25   11.00   10.25   11.25   18.75   18.00   13.75
Payne           19.00   13.25    9.25   12.50   16.00   19.25   16.13
Pittsbur        14.25   11.00   10.25   11.25   18.75   18.00   13.75
Pontotoc        19.00   13.25    9.25   12.50   16.00   19.25   16.13
Pottawat        19.00   13.25    9.25   12.50   16.00   19.25   16.13
RogerMil        19.75   15.88   10.75   15.00   19.13   18.50   14.38
Rogers          14.25   11.00   10.25   11.25   18.75   18.00   13.75
Seminole        19.00   13.25    9.25   12.50   16.00   19.25   16.13
Sequoyah        14.25   11.00   10.25   11.25   18.75   18.00   13.75
Stephens        19.00   13.25    9.25   12.50   16.00   19.25   16.13
Texas           21.25   21.50   18.00   17.50   17.00   18.50   19.00
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| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Tillman | 19.75 | 15.88 | 10.75 | 15.00 | 19.13 | 18.50 | 14.38 |
| Tulsa | 14.25 | 11.00 | 10.25 | 11.25 | 18.75 | 18.00 | 13.75 |
| Wagoner | 14.25 | 11.00 | 10.25 | 11.25 | 18.75 | 18.00 | 13.75 |
| Washing | 14.25 | 11.00 | 10.25 | 11.25 | 18.75 | 18.00 | 13.75 |
| Washita | 19.75 | 15.88 | 10.75 | 15.00 | 19.13 | 18.50 | 14.38 |
| Woods | 19.00 | 13.25 | 9.25 | 12.50 | 16.00 | 19.25 | 16.13 |
| Woodward | 19.00 | 13.25 | 9.25 | 12.50 | 16.00 | 19.25 | 16.13 |

| + | Oct | Nov | Dec | Jan | Feb |
|---|---|---|---|---|---|
| Adair | 14.50 | 15.00 | 14.25 | 16.75 | 13.00 |
| Alfalfa | 15.75 | 17.88 | 18.75 | 18.88 | 18.75 |
| Atoka | 15.75 | 17.88 | 18.75 | 18.88 | 18.75 |
| Beaver | 22.75 | 24.00 | 26.50 | 28.25 | 24.50 |
| Beckham | 14.50 | 19.38 | 21.88 | 21.50 | 18.13 |
| Blaine | 14.50 | 19.38 | 21.88 | 21.50 | 18.13 |
| Bryan | 15.75 | 17.88 | 18.75 | 18.88 | 18.75 |
| Caddo | 14.50 | 19.38 | 21.88 | 21.50 | 18.13 |
| Canadian | 15.75 | 17.88 | 18.75 | 18.88 | 18.75 |
| Carter | 15.75 | 17.88 | 18.75 | 18.88 | 18.75 |
| Cherokee | 14.50 | 15.00 | 14.25 | 16.75 | 13.00 |
| Choctaw | 14.50 | 15.00 | 14.25 | 16.75 | 13.00 |
| Cimarron | 22.75 | 24.00 | 26.50 | 28.25 | 24.50 |
| Clevelan | 15.75 | 17.88 | 18.75 | 18.88 | 18.75 |
| Coal | 15.75 | 17.88 | 18.75 | 18.88 | 18.75 |
| Comanche | 14.50 | 19.38 | 21.88 | 21.50 | 18.13 |
| Cotton | 14.50 | 19.38 | 21.88 | 21.50 | 18.13 |
| Craig | 14.50 | 15.00 | 14.25 | 16.75 | 13.00 |
| Creek | 15.75 | 17.88 | 18.75 | 18.88 | 18.75 |
| Custer | 14.50 | 19.38 | 21.88 | 21.50 | 18.13 |
| Delaware | 14.50 | 15.00 | 14.25 | 16.75 | 13.00 |
| Dewey | 14.50 | 19.38 | 21.88 | 21.50 | 18.13 |
| Ellis | 14.50 | 19.38 | 21.88 | 21.50 | 18.13 |
| Garfield | 15.75 | 17.88 | 18.75 | 18.88 | 18.75 |
| Garvin | 15.75 | 17.88 | 18.75 | 18.88 | 18.75 |
| Grady | 15.75 | 17.88 | 18.75 | 18.88 | 18.75 |
| Grant | 15.75 | 17.88 | 18.75 | 18.88 | 18.75 |
| Greer | 14.50 | 19.38 | 21.88 | 21.50 | 18.13 |
| Harmon | 14.50 | 19.38 | 21.88 | 21.50 | 18.13 |
| Harper | 14.50 | 19.38 | 21.88 | 21.50 | 18.13 |
| Haskell | 14.50 | 15.00 | 14.25 | 16.75 | 13.00 |
| Hughes | 14.50 | 15.00 | 14.25 | 16.75 | 13.00 |
| Jackson | 14.50 | 19.38 | 21.88 | 21.50 | 18.13 |
| Jeffers | 15.75 | 17.88 | 18.75 | 18.88 | 18.75 |
| Johnston | 15.75 | 17.88 | 18.75 | 18.88 | 18.75 |
| Kay | 15.75 | 17.88 | 18.75 | 18.88 | 18.75 |
| Kingfish | 15.75 | 17.88 | 18.75 | 18.88 | 18.75 |
| Kiowa | 14.50 | 19.38 | 21.88 | 21.50 | 18.13 |
| LeFlore | 14.50 | 15.00 | 14.25 | 16.75 | 13.00 |
| Lincoln | 15.75 | 17.88 | 18.75 | 18.88 | 18.75 |
| Logan | 15.75 | 17.88 | 18.75 | 18.88 | 18.75 |
| Love | 15.75 | 17.88 | 18.75 | 18.88 | 18.75 |
| Major | 15.75 | 17.88 | 18.75 | 18.88 | 18.75 |
| Marshall | 15.75 | 17.88 | 18.75 | 18.88 | 18.75 |
| Mayes | 14.50 | 15.00 | 14.25 | 16.75 | 13.00 |
| McClain | 15.75 | 17.88 | 18.75 | 18.88 | 18.75 |
| McCurt | 14.50 | 15.00 | 14.25 | 16.75 | 13.00 |
| McIntosh | 14.50 | 15.00 | 14.25 | 16.75 | 13.00 |
| Murray | 15.75 | 17.88 | 18.75 | 18.88 | 18.75 |
| Muskogee | 14.50 | 15.00 | 14.25 | 16.75 | 13.00 |
| Noble | 15.75 | 17.88 | 18.75 | 18.88 | 18.75 |
| Nowata | 14.50 | 15.00 | 14.25 | 16.75 | 13.00 |
| Okfuskee | 15.75 | 17.88 | 18.75 | 18.88 | 18.75 |
| Oklahoma | 15.75 | 17.88 | 18.75 | 18.88 | 18.75 |
| Okmulgee | 14.50 | 15.00 | 14.25 | 16.75 | 13.00 |
| Osage | 14.50 | 15.00 | 14.25 | 16.75 | 13.00 |
| Ottawa | 14.50 | 15.00 | 14.25 | 16.75 | 13.00 |
| Pawnee | 14.50 | 15.00 | 14.25 | 16.75 | 13.00 |
| Payne | 15.75 | 17.88 | 18.75 | 18.88 | 18.75 |
| Pittsbur | 14.50 | 15.00 | 14.25 | 16.75 | 13.00 |
| Pontotoc | 15.75 | 17.88 | 18.75 | 18.88 | 18.75 |
| Pottawat | 15.75 | 17.88 | 18.75 | 18.88 | 18.75 |

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RogerMil        14.50   19.38   21.88   21.50   18.13
Rogers          14.50   15.00   14.25   16.75   13.00
Seminole        15.75   17.88   18.75   18.88   18.75
Sequoyah        14.50   15.00   14.25   16.75   13.00
Stephens        15.75   17.88   18.75   18.88   18.75
Texas           22.75   24.00   26.50   28.25   24.50
Tillman         14.50   19.38   21.88   21.50   18.13
Tulsa           14.50   15.00   14.25   16.75   13.00
Wagoner         14.50   15.00   14.25   16.75   13.00
Washing         14.50   15.00   14.25   16.75   13.00
Washita         14.50   19.38   21.88   21.50   18.13
Woods           15.75   17.88   18.75   18.88   18.75
Woodward        15.75   17.88   18.75   18.88   18.75
;

************************************************************************************
** The following estimates of annual cost of a harvest unit (in $ per unit)        *
**   were obtained  from:                                                          *
** Thorsell, Sara Renee. "Economies of Size of a Coordinated Biorefinery Feedstock *
**      Harvest System." MS Thesis, Oklahoma State University, May 2003.           *
** The daily capacity of a harvest unit (in tons) was obtained through             *
** consultation with Dr. Huhnke (2005)                                             *
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SCALAR OMEGA "Cost of a Harvest Unit in $ per Unit" /580000/;

SCALAR DCAPHU "Daily Capacity of a Harvest Unit in tons" /341/;

PARAMETER CAPHU(I,M) "Monthly capacity of harvest unit in tons";
        CAPHU(I,M) = FWD(I,M)*DCAPHU;

VARIABLES
  NPW              Net present value for the ethanol production activity
  Q(J,S,G,M)       Commodity g produced at j by facility s in month m
  A(I,KF,M)        Acres of kf in month m in county i
  X(I,KF,M)        Harvested biomass kf in county i month m
  XT(I,J,S,K,M)    Biomass k from i to facility size s at j in month m
  XP(J,S,K,M)      Biomass k processed by facility size s at j in month m
  XSI(I,K,M)       Biomass k stored at source i in month m
  XSIP(I,K,M)      Biomass k going into storage at source i in month m
  XSIN(I,K,M)      Biomass k coming out of storage at source i in month m
  XSJ(J,S,K,M)     Biomass k stored at facility location j in month m
  HU               Number of Harvest Units
  XHU(I,M)         Harvest Unit in county i in month m
  BETA(J,S)        Zero-one variable for plant size s at j;
POSITIVE VARIABLES Q, A, X, XT, XP, XSI, XSIP, XSIN, XSJ, XHU;
BINARY VARIABLE BETA;
INTEGER VARIABLE HU;

EQUATIONS
  OBJ              Objective function
  LANDCON(I,K)     Land constraint for native prairies at county i
  LANDCON2(I)      Constraint for cropland at county i
  XCOMP(I,K,M)     Compute harvested biomass from harvested land
  ACRES0(I,K,M)    "Acres harvested when YAD(K,M)=0"
  BIOSUP1(I,K,M)   First month biomass supply balance at county i
  BIOSUP2(I,K,M)   "Other months' biomass supply balance at county i"
  BIOFLOW(M)       Biomasss flow in each month
  BIOBALI(I,K)     Biomass balance at the supplying county
  PLTCAP(J,S,E,M)  Plant capacity constraints in gallons of ethanol
  STOCAPJ(J,S,M)   Biomass storage capacity constraint at the plant
  BIOXPJ1(J,S,K,M) First month biomass supply at plant location j
  BIOXPJ2(J,S,K,M) "Other months' biomass supply at location j"
  BIOBALJ(J,S,K)   Biomass balance at the plant
  MBINVJ(J,S,M)    Minimum biomass inventory at the plant
  OUTSUP(J,S,G,M)  Output supply constraint
  HUBL(M)          Harvest Units balance
  TTONSHM(I,M)     Capacity of harvest unit in tons by county and month
  LEONT(J,S,G,K,M) Leontief ppf for ethanol and by-products
*  PLTLOC(J)        At most one plant per location
  MXPLT            Max of one plant ;
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OBJ..  NPW =E= {SUM[M,(SUM((J,S,G), RHO(G)*Q(J,S,G,M))
               -SUM((J,S), Q(J,S,"Ethanol",M)/IOE)*GRDIES*(DIEPRI-DIEPRI0)
               -SUM((I,K), TPOC(K)*SUM(KF$KKF(K,KF), A(I,KF,M)))
               -SUM((I,KF), NCOST(KF)*A(I,KF,M))
               -SUM((I,J,S,K), TAU(I,J)*XT(I,J,S,K,M))
               -SUM((I,K), GAMMA(K)*XSIP(I,K,M))
               -SUM((I,K), PSI(K)*SUM(KF$KKF(K,KF), X(I,KF,M))))]
               -SUM((J,S,FT), TAFC(S,FT)*BETA(J,S))
               -OMEGA*HU}*PVAF;

LANDCON(I,K)$(ORD(K) NE 13)..      SUM(KF$KKF(K,KF), SUM(M, A(I,KF,M)))
                                   -CURACRES(I,K) - CCURACRES(I,K) =L=0;

LANDCON2(I)..          SUM(M, SUM(K$CRS(K), SUM(KF$KKF(K,KF),A(I,KF,M))))
                       -BIPROP*POTACRES(I,"Cropland") =L= 0;

XCOMP(I,K,M)..                   SUM(KF$KKF(K,KF), X(I,KF,M))-
                                   SUM(KF$KKF(K,KF), A(I,KF,M)*
                                   BYLD(I,KF))*YAD(K,M)=E=0;

ACRES0(I,K,M)$(YAD(K,M) EQ 0)..  SUM(KF$KKF(K,KF), A(I,KF,M))=E=0;

BIOSUP1(I,K,M)$M1(M)..             SUM(KF$KKF(K,KF), X(I,KF,M))
                                   +THETAI(K)*XSI(I,K,"Feb")
                                   -SUM((J,S), XT(I,J,S,K,M))-XSI(I,K,M)=E= 0;

BIOSUP2(I,K,M)$M2(M)..             SUM(KF$KKF(K,KF), X(I,KF,M))
                                   +THETAI(K)*XSI(I,K,M-1)
                                   -SUM((J,S), XT(I,J,S,K,M))-XSI(I,K,M) =E= 0;

BIOFLOW(M)..               SUM([I,KF], X(I,KF,M))-SUM([I,J,S,K], XT(I,J,S,K,M))
                           +SUM([I,K], XSIN(I,K,M))-SUM([I,K], XSIP(I,K,M))=E= 0;

BIOBALI(I,K)..                     SUM(KF$KKF(K,KF), SUM(M, X(I,KF,M)))
                                   -SUM([J,S,M], XT(I,J,S,K,M))
                                   -(1-THETAI(K))*SUM(M, XSI(I,K,M)) =E=0;

PLTCAP(J,S,E,M)..                  Q(J,S,E,M)-CAPP(S)*BETA(J,S)=L=0;

STOCAPJ(J,S,M)..                   SUM(K, XSJ(J,S,K,M))
                                   -CAP(S,"STORAGE")*BETA(J,S)=L=0;

BIOXPJ1(J,S,K,M)$M1(M)..           SUM(I, XT(I,J,S,K,M))
                                   +THETAJ(K)*XSJ(J,S,K,"Feb")
                                   -XSJ(J,S,K,M)-XP(J,S,K,M) =E= 0;

BIOXPJ2(J,S,K,M)$M2(M)..           SUM(I, XT(I,J,S,K,M))
                                   +THETAJ(K)*XSJ(J,S,K,M-1)
                                   -XSJ(J,S,K,M)-XP(J,S,K,M) =E= 0;

BIOBALJ(J,S,K)..                   SUM([I,M], XT(I,J,S,K,M))
                                   -(1-THETAJ(K))*SUM(M, XSJ(J,S,K,M))
                                   -SUM(M, XP(J,S,K,M))=E=0;

MBINVJ(J,S,M)..                    SUM(K, XSJ(J,S,K,M))-BINV(S)*BETA(J,S)=G=0;

OUTSUP(J,S,G,M)..                  Q(J,S,G,M)
                                   -SUM(K, LAMBDA(K,G)*XP(J,S,K,M))=L= 0;

HUBL(M)..                        SUM(I, XHU(I,M)) - HU =L= 0;

TTONSHM(I,M)..                SUM(KF, X(I,KF,M)) - (XHU(I,M)*CAPHU(I,M)) =L= 0;

LEONT(J,S,G,K,M)..                 Q(J,S,"Ethanol",M)*LAMBDA(K,G) -
                                   Q(J,S,G,M)*LAMBDA(K,"Ethanol") =E= 0;

*PLTLOC(J)..                        SUM(S, BETA(J,S)) =L= 1;

MXPLT..                        SUM([J,S], BETA(J,S)) =L= 1;
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MODEL Ethanol /ALL/;

SOLVE Ethanol MAXIMIZING NPW USING MIP;

DISPLAY RHO, BETA.L, Q.L, XP.L, XSJ.L, XT.L, X.L, XSI.L, XSIN.L, XSIP.L,
        A.L, CRUDPRI;

***RESULTS SUMMARY***

PARAMETER TOTLAND Total land producing biomass;
  TOTLAND(K,M) = SUM(KF$KKF(K,KF), SUM(I, A.L(I,KF,M)));

PARAMETER TLANDM Total land producing biomass by month;
  TLANDM(M) = SUM([I,KF], A.L(I,KF,M));

PARAMETER TLANDK Total land producing biomass by biomass type;
  TLANDK(K) = SUM(KF$KKF(K,KF), SUM([I,M], A.L(I,KF,M)));

PARAMETER TLANDRK Total area harvested annually by region and feedstock type;
  TLANDRK(R,K) = SUM(I$IR(I,R), SUM(KF$KKF(K,KF), SUM(M, A.L(I,KF,M))));

PARAMETER TLANDR Total area harvested annually by region;
  TLANDR(R) = SUM(K, TLANDRK(R,K));

PARAMETER TOTBIO Total biomass to be made available annually (tons);
  TOTBIO = SUM([I,KF,M], X.L(I,KF,M));

PARAMETER MBIOHAR Total biomass harvested by month;
  MBIOHAR(M) = SUM([I,KF], X.L(I,KF,M));

PARAMETER TBIOK Total biomass harvested by biomass type;
  TBIOK(K) = SUM(KF$KKF(K,KF), SUM([I,M], X.L(I,KF,M)));

PARAMETER IKBIOHAR Total biomass harvested by month;
  IKBIOHAR(I,K) = SUM(M, SUM(KF$KKF(K,KF), X.L(I,KF,M)));

PARAMETER MBIOSTO Total biomass stored at counties by month;
  MBIOSTO(M) = SUM([I,K], XSI.L(I,K,M));

PARAMETER MBIOSTON Total biomass going in storage at counties by month;
  MBIOSTON(M) = SUM([I,K], XSIP.L(I,K,M));

PARAMETER MBIOSHIP Total biomass shipments by month;
  MBIOSHIP(M) = SUM([I,J,S,K], XT.L(I,J,S,K,M));

PARAMETER BIOSHIP Biomass shipments from counties to plants by type and month;
  BIOSHIP(K,M) = SUM([I,J,S], XT.L(I,J,S,K,M));

PARAMETER BIOSHIPIJ Biomass shipments from county i to plant j;
  BIOSHIPIJ(I,J) = SUM([S,K,M], XT.L(I,J,S,K,M));

PARAMETER PLTR Optimal plant locations by region;
  PLTR(J,R)$JR(J,R) = SUM(S, BETA.L(J,S));

PARAMETER MBIOSTJ Total biomass stored onsite;
  MBIOSTJ(M) = SUM([J,S,K], XSJ.L(J,S,K,M));

PARAMETER PROPCAPM "Plant monthly capacity usage (percent)";
  PROPCAPM(J,S,M) = 100*Q.L(J,S,"Ethanol",M)/CAPP(S);

PARAMETER PROPCAP "Plant monthly capacity usage (percent)";
  PROPCAP(J,S) = 100*SUM(M, Q.L(J,S,"Ethanol",M))/(12*CAPP(S));

DISPLAY TOTLAND, TLANDM, TLANDK, TLANDRK, TLANDR, TOTBIO, MBIOHAR, TBIOK,
        IKBIOHAR, MBIOSTO, MBIOSTON, MBIOSHIP, BIOSHIP, BIOSHIPIJ, PLTR, MBIOSTJ,
        PROPCAPM, PROPCAP;

************************************************************
*Partitioning total costs into its components              *
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PARAMETER PRODCO "Total feedstock production/procurement costs in $";
  PRODCO = SUM([I,K,M], TPOC(K)*SUM(KF$KKF(K,KF), A.L(I,KF,M)));

PARAMETER LDCO Land rent and opportunity cost of crop residues in $;
  LDCO = SUM([I,K,M], POC(K,"Landrent")*SUM(KF$KKF(K,KF), A.L(I,KF,M)))
            +SUM([I,K,M], POC(K,"Biopcost")*SUM(KF$KKF(K,KF), A.L(I,KF,M)));

PARAMETER ESMCO "Establishment/maintenance cost, w/o landrent or cost of N";
  ESMCO = PRODCO - LDCO;

PARAMETER NITCO Total cost of nitrogen fertilizer in US $;
  NITCO = SUM([I,KF,M], NCOST(KF)*A.L(I,KF,M));

PARAMETER FLDCO "Total field costs, excluding landrent & cost of crop residues";
  FLDCO = ESMCO + NITCO;

PARAMETER TPTCO Total cost of transporting the feedstocks;
  TPTCO = SUM([I,J,S,K,M], TAU(I,J)*XT.L(I,J,S,K,M));

PARAMETER STORCO Total cost of storing biomass in the field;
  STORCO = SUM([I,K,M], GAMMA(K)*XSIP.L(I,K,M));

PARAMETER FXDCO(FT) Fixed costs by facility type;
  FXDCO(FT)$(ORD(FT) EQ 1) = SUM([J,S], TAFC(S,"STORAGE")*BETA.L(J,S))
                               +SUM([J,S,M], Q.L(J,S,"Ethanol",M)/IOE)
                                 *GRDIES*(DIEPRI-DIEPRI0);
  FXDCO(FT)$(ORD(FT) EQ 2) = SUM([J,S], TAFC(S,"PROCESS")*BETA.L(J,S));

PARAMETER TFXDCO Total fixed costs;
  TFXDCO = SUM(FT, FXDCO(FT));

PARAMETER HRVUNTS   Harvest Units to be purchased;
        HRVUNTS = HU.L;

PARAMETER HARVCO Total Cost of Harvesting using Harvest Units;
         HARVCO = OMEGA*HU.L;

PARAMETER TPSI Total Biomass Purchase Cost in $ per ton;
         TPSI = SUM([I,K,M], PSI(K)*SUM(KF$KKF(K,KF), X.L(I,KF,M)));

DISPLAY LDCO, FLDCO, STORCO, TPTCO, FXDCO, TFXDCO;

DISPLAY ESMCO, NITCO, PRODCO, HRVUNTS, HARVCO, TPSI;
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# VITA

Lawrence Daniel Mapemba

Candidate for the Degree of

Doctor of Philosophy

Thesis: COST TO DELIVER LIGNOCELLULOSIC BIOMASS TO A BIOREFINERY

Major Field: Agricultural Economics

Biographical:

Personal Data: Born in Blantyre, Malawi, on June 3, 1969, to Lawrence and Margaret Mapemba.

Education: Graduated from Salima Secondary School, Salima, Malawi in June 1984; received Bachelor of Science degree in Agriculture from University of Malawi, Lilongwe, Malawi in September 1993; Master of Science in Agricultural Economics from Oklahoma State University, Stillwater, Oklahoma in August, 2002. Completed the requirements for the Doctor of Philosophy degree in Agricultural Economics at Oklahoma State University in July, 2005.

Experience: Graduate Research Assistant, Department of Agricultural Economics, Oklahoma State University, 2001-2005; Senior Agricultural Economist, Planning Division, Ministry of Agriculture and Irrigation, 1997 to present, Lilongwe, Malawi; Agricultural Economist, Estate Land Utilization Study, 1995-1997, Lilongwe, Malawi; Secondary School Teacher, St. John’s Secondary School, 1993-1995, Lilongwe, Malawi.

Professional Membership: American Agricultural Economics Association; Southern Agricultural Economics Association; The Honor Society of Phi Kappa Phi.

Name: Lawrence Daniel Mapemba Date of Degree: July, 2005

Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of Study: COST TO DELIVER LIGNOCELLULOSIC BIOMASS TO A BIOREFINERY

Pages in Study: 253 Candidate for the Degree of Doctor of Philosophy

Major Field: Agricultural Economics

Scope and Method of Study: The purpose of this study was to determine the cost to deliver a continuous flow of lignocellulosic biomass (LCB) to a biorefinery that can process 1,000, 2,000 or 4,000 tons of biomass per day. The study also sought to determine how the method of modeling harvest and procurement cost of biomass changes the cost to deliver a steady flow of biomass to a biorefinery. Lignocellulosic biomass includes agricultural residues (e.g. corn stover and wheat straw), herbaceous crops (e.g. alfalfa, switchgrass) and improved pastures (old world bluestem, tall fescue and bermuda grass). A mixed integer mathematical programming model was developed to determine the optimal size and location of a biorefinery, the quantity and types of biomass to be used, sources of biomass feedstock, monthly harvest and storage quantities, number of harvest machines to be used, and the cost to deliver a steady flow of biomass to a biorefinery, among other variables of interest. The base model has more than 403,000 activities in 48,400 equations.

Findings and Conclusions: Based on this study an LCB biorefinery business is expected to develop in concert with well coordinated biomass feedstock harvest units. The harvest units would be managed either by the biorefinery industry itself or by a private company. A total of 26 harvest units at an average investment of $15.34 million would be required to harvest biomass feedstock for a large plant (i.e. plant with capacity to process 4,000 dry tons of biomass per day). These harvest units would result in a per ton harvest cost of $10.72. The biomass industry may use a variety of biomass feedstock species that mature at different periods during the year. In the model total of seven biomass feedstock types were used including wheat straw, corn stover, old world bluestem, bermuda grass, native tall grass, native short grass, and mixed native grass. A variety of biomass feedstock types would result in a harvest season of nine months. This would result in a lower cost to deliver LCB to a biorefinery than a shorter harvest season. Since the plant would operate throughout the year a short harvest season would result in large storage reserves for long periods leading to high storage costs. For the assumptions used it was determined that feedstock would be hauled from an average radius of 106 miles to the biorefinery.

ADVISER'S APPROVAL: Francis Epplin