DAYS AVAILABLE FOR HARVESTING SWITCHGRASS AND THE COST TO DELIVER SWITCHGRASS TO A BIOREFINERY

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CHAPTER I

INTRODUCTION

Background of This Study

The U.S. Energy Policy Act of 2005 includes a provision (goal) that beginning in 2013, a minimum of 250 million gallons per year of ethanol be produced from lignocellulosic sources including crop residues and perennial grasses such as switchgrass.[1] If lignocellulosic biomass (LCB) materials are to become a major feedstock for unsubsidized ethanol production, an economically viable production and conversion system must be designed. Previous studies have found that the cost of harvesting feedstock is a key cost component.

Most studies have modeled LCB harvest cost in a manner similar to forage harvest cost. The quality and value of harvested forage such as alfalfa for livestock feed is a function of its nutrient content, especially protein, which means that the timing of harvest is critically important. In other words, the length of the harvest season is expected to be narrow. However, for a biorefinery that uses a gasification-fermentation process, the key component of the LCB is the mined atmospheric carbon contained in the

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[1] The term lignocellulosic is a compound word including both lignin and cellulose. Lignin represents the strength and rigidity of plants and cellulose is the chief constituent of the cell wall in all green plants. Lignocellulosic biomass (LCB) generally refers to waste from wood products processing, crop residue, and perennial grasses (Epplin, Mapemba, and Tembo 2005).

lignin and cellulose.[2] Hence, the window for harvest is expected to be relatively lengthy since the timing of harvest is not as critical. Thorsell et al. (2004) found that if a biorefinery could use a variety of LCB feedstock that had wide harvest windows, harvest costs could be substantially lower than estimates based upon farm-sized operations designed to harvest forage for livestock use and that a coordinated harvest unit could result in substantial size economies.

Epplin, Mapemba, and Tembo (2005) assumed that switchgrass could be harvested in Oklahoma from July through February of the following year. They found that the estimated harvest cost varied from $25 per ton for a four month harvest season to $11 per ton for an eight month harvest season. A wide harvest window enables the use of harvest machines and harvest crews throughout the harvest season, and fixed costs of harvest machines can be spread over many months. A wide harvest window reduces the fixed costs of harvest machinery per ton of feedstock. These results have shown that the length of the harvest season is a significant issue to determine the cost to harvest LCB feedstock.

Epplin, Mapemba, and Tembo (2005) did not have refined estimates of the number of days per month that LCB could be harvested. They based their estimates of available harvest days per month on a study conducted in 1973 designed to determine the number of days per month that farmers in southwestern Oklahoma could conduct tillage operations (Reinschmiedt 1973). To determine more precise estimates of the number of harvest machines required to harvest and provide LCB to a biorefinery, and more precise

[2] A biorefinery is a facility that processes and converts biomass into value-added products. These products can range from biomaterials to fuels such as ethanol or important feedstocks for the production of chemicals and other materials. Biorefineries can be based on a number of processing platforms using mechanical, thermal, chemical, and biochemical processes (Perlack et al. 2005, p. 44).

estimates of harvest costs, more precise estimates of the number of LCB harvest days per month would be required. A reasonably precise estimate of the number of harvest days would also be necessary to determine the number of harvest machines required to support a biorefinery.

Problem Statement

In farming operations, a correct decision about the appropriate harvest mechanization system capacity is important. A large set of machinery may enable quick completion of field work, but may result in high capital costs for depreciation, interest, and other ownership costs, while a smaller machinery set will reduce these costs, but may not be sufficient to complete the job on time, which could result in yield losses from late harvesting or increased harvesting costs per acre (Babeir, Colvin, and Marley 1986; McGechan et al. 1989; ISU 2001). Cost conscious farmers will choose the size of their farm machinery based on the number of field workdays to do the required work (Enz, Helm, and Brenk 1991). Therefore, for efficient machinery management, a farmer needs information on the number of field workdays available to properly balance between the timeliness costs of an inadequate system and the inflated capital costs of over-investment in machinery (Hayhoe 1980).

Interest in use of perennial grasses and crop residues as renewable sources of biomass for energy has inspired research to determine the economic feasibility of producing ethanol from LCB. Ultimately, the economic viability of ethanol production from LCB feedstock such as perennial grasses depends in part on the cost to produce, harvest, and deliver feedstock to the ethanol production facilities (Thorsell et al. 2004).

However, a well-developed harvesting and transportation system does not exist for perennial grasses and crop residues. While some farmers have forage harvest machines and equipment that might be used to harvest perennial grasses, 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 feedstock to ethanol production facilities throughout the year (Mapemba and Epplin 2004). Consequently, inappropriate harvesting machinery capacity could overestimate or underestimate the cost of delivering LCB to biorefineries.

Determining the time available for required harvest operations is an essential prerequisite to optimization of harvest cost. It is difficult to estimate the number of field workdays because agricultural field work is strongly weather dependent. Variations in weather have an impact on soil workability. For example, high moisture content of soil resulting from rainfall causes excessive wheel slippage, which may reduce a tractor's effective pulling power and increase the risk of damage to soil structure, thereby preventing harvest operations (Dyer and Baier 1979; Simalenga and Have 1992). Another issue is that safe storage of baled grasses requires a dry matter content of 85 percent. Hence, the moisture content of cut grasses on the ground must be considered prior to baling. The period of drying required after cutting and prior to baling is also influenced by weather variations. For instance, under weather conditions with low air humidity and strong sunlight, drying of cut grasses may proceed rather quickly. However, during an extended period of rain, it may be necessary to leave cut material on the ground for a long period to enable the necessary reduction in dry matter content necessary for safe baling.

Therefore, to determine a more accurate estimation of the cost to harvest LCB, the number of field workdays considering both mowing and baling operations of LCB such as switchgrass are considered. However, published studies on the estimation of number of workdays for harvesting LCB feedstock cannot be found. And, LCB harvest day estimates are not available for Oklahoma.

Objectives of the Study

General Objective:

Estimate the number of suitable field workdays per month in which switchgrass can be harvested in Oklahoma at different probability levels.

Specific Objectives:

(1) To develop a general soil moisture balance model.

(2) To develop a drying model of switchgrass on the ground after cutting.

(3) To determine the probability distribution of the number of suitable field workdays per month.

(4) To determine how the number of field workdays for the mowing operation and baling operation can be incorporated into the model developed by Mapemba.

(5) To determine the optimal number of harvest machines for a biorefinery located in Oklahoma, the cost to procure, harvest, store, and transport a flow of switchgrass feedstock to a 1,000, 2,000, 3,000, and 4,000 dry tons of biomass per day biorefinery, and how restrictions of number of workdays influence cost.

Extensions from Prior Studies

This study is extended from prior studies in several areas. First, to our best knowledge no prior study has sought to determine the number of days per month that switchgrass could be harvested for use as biorefinery feedstock. Most prior studies of field workdays have been designed to determine the number of days that tillage work could be conducted.

Second, this study uses estimates of crop evapotranspiration based upon daily weather data for calculating a soil moisture budget. In prior studies reference evapotranspiration or potential evapotranspiration which is measured by the mass transfer of water from the cropped surface has been used to compute a soil moisture budget.[3] In prior studies, even though a particular crop is considered, the same value of evapotranspiration has been incorporated into the soil moisture budget model regardless of crop without considering unique crop characteristics such as crop height and leaf size. Therefore, the reason for a particular crop being considered in prior studies for computing the number of field workdays was for consideration of the period of seeding or harvesting but not for consideration of properties of a particular crop. This study is the first attempt

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[3] Evapotranspiration (ET) is defined as the amount of water that evaporates from vegetation (transpiration) and from the underlying soil. Reference evapotranspiration is the ET that occurs from an extensive surface of green grass of uniform height, actively growing, well-watered, and completely shading the ground. That is, reference evapotranspiration is defined as the ET that occurs from a standardized "reference" crop such as clipped grass or alfalfa. Common usage in the United States and elsewhere has been to use the two reference crops of clipped grass (cool season varieties) and full-cover alfalfa (lucerne). Potential evapotranspiration is a measure of the ability of the atmosphere to remove water from wet soil and plant surfaces expressd as the rate of latent heat transfer per unit area. Note that in the definition of potential evapotranspiration, the evapotranspiration rate is not related to a specific crop. (Jensen, Burman, and Allen 1990; Allen et al. 1998; Irmak and Haman 2007).

among the studies computing the number of field workdays considering the properties of switchgrass.

Third, in addition to considering tractability, where tractability refers to the ability of a field to permit efficient movement of farm machines without soil structural damage, this study considers the moisture content of cut grasses after mowing as a decision factor. To our knowledge, this is the first attempt to model the number of harvest days dependent on both tractability and moisture content of switchgrass after cutting.

Fourth, this study is also the first attempt to determine the number of switchgrass harvest days for Oklahoma. In 1973 Reinschmiedt studied the number of field workdays for tillage. However, Reinschmiedt's study considered only southwestern Oklahoma (nine counties). This study considers all regions of Oklahoma.

Fifth, Mapemba (2005) and Mapemba et al. (2007) assumed that each day suitable for mowing was also suitable for baling LCB. However, this study recognizes that the number of workdays for mowing and those suitable for baling may be different. It is essential that the moisture content of cut material be no greater than 15 percent for safe baling in large rectangular solid bales. Hence, the number of days that switchgrass may be safely baled could be substantially less than the number of days that standing switchgrass may be mowed. This study is designed to determine days suitable for mowing and an independent estimate of days suitable for baling.

Sixth, Mapemba (2005) incorporated a coordinated set of harvest machines, including mowers, rakes, balers, tractors, and a bale transporter and harvest crew (called harvest unit) designed by Thorsell (2003), that provides an integrated capacity of harvest as a given number of tons of biomass into his model. His model endogenously determined the optimal number of harvest units regardless of types of harvest operation. Mapemba (2005) assumed that a single harvest unit provides a capacity of 340.67 tons per day throughout a year. For instance, suppose that the optimal number of harvest units is ten. The ten Thorsell harvest units, that include 30 mowers and 30 balers, would be selected as necessary to harvest switchgrass even though hours suitable for mowing may differ from hours suitable for baling. The discrepancy between the number of workdays suitable for mowing and the number suitable for baling may result in a different optimal mowing and baling capacity. In addition, harvest capacity varies across months with the length of day light. This study is designed to determine independently the optimal number of harvest units for mowing and for baling.

CHAPTER II

LITERATURE REVIEW

The purpose of this chapter is to present a very brief description of a number of prior attempts to model field workdays. Studies that have addressed conditions necessary for harvesting biomass and modeling of days suitable for biomass harvest are also described. Ideally a researcher could build probability distributions of field workdays and biomass harvest days from actual observations for the location of interest. However, the author was unable to locate any observed data over time for field workdays and biomass harvest days for Oklahoma.

Predicting Field Workdays with Soil Moisture Budgeting Technique

Due to the lack of recorded actual farm data for workdays and days suitable for biomass harvest, a number of models have been developed to determine the number of suitable days for conducting field work on farms. Most prior attempts to model days suitable for field work have used a similar method. They have assumed that workdays are a function of soil moisture content, which is influenced by meteorological factors. Soil moisture content was modeled over time and some critical soil moisture condition was set to determine whether a given field operation could be performed on a given day

(Shaw 1966; Bolton et al. 1968; Rutledge and McHardy 1968; Frisby 1970; Selirio and Brown 1972; Baier 1973; Kish and Privette 1974; Ayres 1975; Hassan and Broughton 1975; Elliott, Lembke, and Hunt 1977; Dyer and Baier 1979; Rosenberg et al. 1982; Rotz and Harrigan 2004).

Shaw (1966) considered the number of workdays per week during the spring season (March to May) for Ames, Iowa using a soil moisture budgeting technique based on daily precipitation and evaporation. He calculated evaporation from temperature and cloud cover, and specified several combinations of temperature and precipitation that would cause either freezing or thawing of the soil. For instance, 0.15 inch loss of soil moisture was found to occur on days with no cloud cover. He assumed that saturated soils contained 1.4 inches of moisture in the top six inches of the soil profile and soil was workable on days when it was not frozen and the available soil moisture in the top six inches of the profile was less than or equal to 0.75 inches.

Ayres (1975) predicted workdays for corn harvesting in Iowa, by adapting the model developed by Shaw. Using temperature, precipitation, snowfall, and freezing of the soil, he predicted days that were suitable for fall tillage operations. He also estimated the probability of suitable days for field work using a first order Markov chain.

Bolton et al. (1968) estimated field workdays for clay and sandy soils in the Mississippi river delta cotton area using a soil moisture balance model. They used evapotranspiration in their model, which was estimated from a regression model that includes temperature and time of year as independent variables. They assumed that a clay soil was workable when it contained no more than 2.11 inches of water in the surface six inches. For sandy soils, they defined a day unsuitable for field work when 1.48 inches of water or more was in the surface six inches.

The Thornthwaite method (Thornthwaite 1948) for estimating potential evapotranspiration was applied to the soil moisture balance model by several researchers (Kish and Privette 1974; Elliot, Lembke, and Hunt 1977). This method estimates potential evapotranspiration using mean air temperature, day length and the latitude of the area considered. Since it was easy to compute a potential evapotranspiration, the method was widely used even though it was found to be unsatisfactory.

Kish and Privette (1974) developed a soil moisture balance model to predict workdays for soil tillage in South Carolina. Precipitation and potential evapotranspiration were used to compute the soil moisture content that was recorded as a percentage of moisture content at field capacity[4]. If this moisture content on a given day was less than the threshold value of moisture content that determines workability, the day was classified as a workday. The field capacity and threshold values of moisture content were varied by soil types.

Elliot, Lembke, and Hunt (1977) considered not only precipitation and evapotranspiration but also runoff, drainage, crop cover, and persistence of rainwater to develop a soil moisture balance model for Illinois soils for the spring season. They used percentage of available soil moisture in the upper 150 mm (six inches) of soil as a tillage criterion, 80 percent for fine sandy loam soils, and 90 percent for silt loam soils. They verified the model using field workdays from the Illinois Cooperative Crop Reporting Service and local daily field observations of favorable workdays and they concluded that

[4] Field capacity is the percentage of water remaining in a soil two days after having been saturated and after free drainage has practically ceased (the percentage may be expressed on the basis of weight or volume) (Hassen and Broughton 1975).

there was no significant difference between the actual and estimated number of working days on a monthly basis.

Rutledge and McHardy (1968), Selirio and Brown (1972), Baier (1973), and Dyer and Baier (1979) used a versatile soil moisture budget developed by Baier and Robertson (1966). The soil was divided into six moisture zones, each zone holding a fixed depth of water at field capacity. In an attempt to make the budget independent of soil type, the thickness of each layer was varied in proportion to its moisture holding capacity. The moisture contents of each zone were then determined from daily precipitation and potential evapotranspiration. Rutledge and McHardy (1968) concluded that a satisfactory correlation with observed days suitable for tillage occurred when 95 percent of the available water capacity was used as the maximum soil moisture content in the top six inches, with the restriction of no snow on the ground.

Selirio and Brown (1972) estimated spring workdays in Ontario. They concluded that cultivation was possible when the soil moisture content was about 90 percent of the field capacity value to a depth of 12 cm (4.7 inches) regardless of soil moisture content in the lower zones. They assumed a day to be suitable for field work if the top 12 cm of the soil was at or below 90 percent of field capacity, daily snowfall was less than 25 mm (one inch), and maximum air temperature was above 0°C.

Baier (1973) and Dyer and Baier (1979) developed soil tractability models. Baier (1973) defined a field workday as a day with no snow cover and with estimated soil moisture conditions in upper three zones, as shown in Table 1.

Table 1. Criteria for a Field Work Day Based on Estimated Soil Moisture in the Upper Three Zones

Soil moisture notation (% of field capacity)	Zone	Depth of Zone (inches)	Field capacity (inches)	Work-day criteria: no snow on ground; % of field capacity
SM 97.5	1	0-2	0.4	≤ 97.5
	2	2-6	0.6	≤ 97.5
	3	6-10	1.0	≤ 97.5
SM 90/95	1	0-2	0.4	≤ 90.0
	2 and 3	2-10	1.6	≤ 95.0

Source: Baier (1973)

Rosenberg et al. (1982) used weather and soil data to predict the days suitable for field work in Michigan considering soil moisture, soil physical state and tractability. They extended Tulu et al.'s (1974) model and used Rutlege and Mchardy's (1968) "go" "no-go" criteria. A day was classified to be a "no-go" day if soil moisture content in the top 15.2 cm (six inches) of soil was above 95 percent available water holding capacity. For sandy soils, the criterion was 99 percent.

Frisby (1970) used a soil moisture budgeting technique and an equation for the drying rate of soil at moisture contents above field capacity developed by Peterson and Frisby (1969) for predicting the number of days available for primary tillage in the spring and fall for a soil in central Missouri. He considered a day as suitable for tillage if the soil moisture content was equal to or less than field capacity and if precipitation was less than one inch.

Rotz and Harrigan (2004) used a soil moisture budget model developed by Jones and Kiniry (1986). In this model, precipitation, runoff, evapotranspiration, moisture migration, and drainage are tracked through time to predict the moisture content in multiple layers of the soil profile and soil type, moisture bulk density, and surface albedo are considered to determine water holding capacity. They used different tractability conditions by soil types and farm operations, as shown in Table 2.

Table 2. Recommended Tractability Coefficients by Operation and Soil Type

Soil type	Spring tillage		Fall tillage		Fall harvest	
	Upper	Lower	Upper	Lower	Upper	Lower
Clay loam	0.92	0.94	0.99	1.00	1.03	1.01
Loam	0.94	0.96	1.02	1.03	1.04	1.02
Sandy loam	0.96	0.98	1.03	1.05	1.06	1.04
Loamy sand	1.00	1.00	1.04	1.04	1.08	1.06

Note: Upper: Top 75mm (three inches) of soil profile; Lower: 75 to 150mm depth in soil profile
Source: Rotz and Harrigan (2005)

Hassan and Broughton (1975) found that tractability criteria for seedbed preparation appeared to be affected by the moisture state in the upper 25 mm (one inch) and second 51 mm (two inches) of the soil profile based on limited field observations. The limiting percentage of field capacity in the upper 25 mm and next 51 mm of soil profile for clay, clay loam and sandy loam soils of McDonald College Farm, St. Lawrence Lowlands, Quebec, Canada were recorded by them to be 10, 97; 50, 93; and 66, 98.2; respectively.

Reinschmiedt (1973) surveyed farmers to obtain relationships between rainfall and tractability for a machinery selection study in Oklahoma. Sixty-nine farmers in nine Southwestern Oklahoma counties responded to a questionnaire that satisfied the responses by four seasons and three soil types. The respondents were asked to provide an estimate of the days delay that different combinations of rainfall would produce. For each of four rainfall totals that occurred “today at noon”, the farmers were asked to estimate the number of days that tillage would be delayed for seven different rainfall histories.

Table 3. Time-Loss Tableau for Loam Soils

Season	Today's Rainfall (inch)	Previous field moisture conditions						
		I	II	III	IV	V	VI	VII
June~ August	0.25	0.17	0.22	0.56	0.54	0.80	0.60	1.23
	0.50	0.33	0.43	0.97	0.93	1.27	0.84	2.10
	1.00	0.97	1.03	1.85	1.76	2.34	1.53	2.57
	1.75	1.94	2.07	2.80	2.53	3.17	2.67	3.97

Note: I: Previous two weeks have been dry (no rain).
II: 1.5 inches of rain fell ten days ago.
III: 2 inches of rain fell five days ago.
IV: 1 inch fell of rain three days ago.
V: 2 inches of rain fell three days ago.
VI: 0.5 inch of rain fell yesterday.
VII: 1.5 inches of rain fell yesterday.
Source: Reinschmiedt (1973)

Table 3 includes the time-loss tableau for loam soil for Southwestern Oklahoma estimated by Reinschmiedt. According to table 3, if today's rainfall is 0.5 inches and 1.5 inches of rain fell yesterday the estimate of days lost is 2.1, as reported in column VII.

Drying Rate of Cut Grasses

A number of models have been proposed to predict the moisture content of cut grasses using weather data. These models can be classified into two approaches. One is a mechanistic approach using physical law based on the Penman-Monteith equation (Brück and Elderen 1969; Thompson 1981; Smith et al. 1988; Atzema 1992). The other is an empirical approach using statistical methods such as regression that are based on the initial, the final, or the equilibrium moisture content of cut grasses (Hayhoe and Jackson

1974; Hill 1976; Dyer and Brown 1977; Pitt 1984; Rotz and Chen 1985; Rotz 1985; Gupta et al. 1989; Savoie and Beauregard 1990; Akkharath and Gupta 1997).

Brück and Elderen (1969) modeled the field drying of grass hay and wheat based on simulations of evapotranspiration of living plants with hourly inputs of meteorological data. Thompson (1981) developed the theoretical model of field drying of cut grasses based on the Penman-Monteith equation. By incorporating meteorological variables into this model, he predicted the loss of moisture from a hay swath.

Smith et al. (1988) revised Thompson's model and extended it to include the effect of forced convection, windrow thickness, and mechanical conditioning. However, since weather parameters used in these models are not available at standard weather stations, Thompson and Smith et al.'s models are not universally applicable.

To make up for the shortcoming of these models, Atzema (1992) modified Brück and Elderen (1969)'s drying model based on the Penman-Monteith equation by incorporating weather variables measured by standard weather stations. Although these models are sound theoretically, the complexity of the equations and lack of meteorological data constrain their use in practical field situations.

According to Wright et al. (2001), empirical models using statistical estimates are simpler and more applicable than mechanistic models. In addition, empirical models are not restricted to a limited range of weather and management conditions. A number of researchers have modeled change in moisture content of cut grasses as an exponentially decaying function (Hayhoe and Jackson 1974; Hill 1976; Pitt 1984; Rotz and Chen 1985; Rotz 1985; Savioe and Beauregard 1990).

Hayhoe and Jackson (1974) proposed a hay drying equation based on the accumulation of potential evaporation. They estimated statistical coefficients to predict drying of a mowed alfalfa (25%) and timothy (75%) mix.

Hill (1976) expressed a drying curve based upon moisture ratio rather than moisture content. The moisture ratio was defined as the moisture remaining to be lost after any *t* hours divided by total moisture to be lost when equilibrium is reached. He proposed that the exponential decay curve of the moisture ratio was a function of drying condition. He used regression to estimate drying conditions for alfalfa from mean saturation vapor pressure deficit. Vapor pressure deficit is the difference between actual vapor pressure deficit and saturated vapor pressure possible at a given ambient air temperature and relative humidity. It is a crude measure of the drying power of the air.

Dyer and Brown (1977) formulated a simulation model of hay drying. This model included the relationship between the rate of moisture loss from hay and rewetting of hay caused by rain and dew.

Pitt (1984) found that for his pan evaporation model, drying constants varied considerably from experiment to experiment so he supplied a method of calculating the parameters under any given set of circumstances.

Rotz and Chen (1985) defined the drying rate of alfalfa as a nonlinear function of solar radiation, dry bulb temperature, vapor pressure deficit, soil moisture content, swath density, and application rate of chemical solution. They showed that drying rate was most heavily influenced by the amount of solar radiation and higher drying rates normally occurred during the first day of drying.

Rotz (1985) developed an alfalfa drying simulation model for a whole-farm diary-forage systems model. For the field curing model he used the field drying model developed by Rotz and Chen (1985) and considered the rewetting which occurs at night. In the rewetting model, the equilibrium moisture content, swath density, rainfall, and moisture absorption rate of hay influence drying rate. Equilibrium moisture content was assumed to be a function of wind velocity and relative humidity and the moisture absorption rate was assumed to be described by the following formula, $4.0 g/m^2$ per hour.

Savoie and Beauregard (1990) modified a model suggested by Rotz and Chen (1985). They used a simple linear model instead of the nonlinear Rotz and Chen model. They included solar radiation, air dry bulb temperature, windrow density, and hay manipulation treatment such as tedding as factors that influence drying rate. Their model also showed that solar radiation was the most important drying rate factor and that a tedding treatment enhanced drying rate.

Gupta et al. (1989) worked on the development of a drying model for unconditioned and mechanically conditioned pasture hay in Australia. They considered moisture uptake due to rain and dew.

Akkharath and Gupta (1997) also worked on the development of a drying model for alfalfa in Australia. Unlike the model developed by Gupta et al. (1989), they constructed a model with four major management options at time of cutting, i.e. not conditioned, mechanically conditioned, chemically conditioned, and combination of mechanical and chemical conditioned. The variables included in their drying model were similar to those included by Rotz and Chen (1985).

Information gleaned from this review of literature was used to form the conceptual framework that is presented in the next chapter.

CHAPTER III

CONCEPTUAL FRAMEWORK

Prediction of Field Workdays

Suitable field workdays for harvesting are predicted on a daily time step based upon meteorological information. If weather or field conditions allow going out to the field, the day would be considered as a workday. On the contrary, when field conditions do not permit proper field operations, the day would be regarded as a non-workday. Therefore, based on the specific criteria of weather and field conditions, it is determined if a particular day is suitable for field operations or not. Sequences of workdays and non-workdays are grouped, and then summed for months over several years to provide the number of suitable field workdays for each month of each year. Cumulative probability distributions are constructed from these observations. Finally, the number of suitable field workdays for harvesting operations of switchgrass would be provided by each month at different probability levels (Rosenberg et al. 1982).

To determine if a day will be classified as a workday or non-workday, values for several variables are required.

Weather Condition of Field

On a rainy day or snowy day, it is difficult to work in the field with machines so that a rainy day (rainfall > 0mm) or a snowy day (snowfall > 0mm) is classified as a non-workday.

Tractability

Field operations require decisions as to when the soil is tractable or non-tractable. The Canadian Society of Soil Science defined "tractability" by stating that a soil is considered tractable if a tractor or other farm machine can move on that soil to satisfactorily perform the function of the machine, without causing significant damage to the soil (Hassan and Broughton 1975). In other words, tractability is the ability of a field to permit a machine to operate and perform its function without damaging the soil (Babeir, Colvin, and Marley 1986). This ability depends, to a large extent, on the soil moisture content. High moisture content may reduce field tractability and increase the risk of damage to soil structure, thereby preventing machines from operating in the field. At low soil moisture, machines can perform their function because the soil is hard and more coherent due to the cementation effect between the dried particles (Simalenga and Have 1992).

Tractability and, consequently, the number of suitable field workdays are affected by the soil moisture content, which is controlled by the combined influences of soil characteristics and the weather (Rounsevell and Jones 1993). Tractability criteria can be defined and used to differentiate between a "tractable" and "non-tractable" soil condition. These criteria are based on the soil moisture content of top soil layer. The soil moisture criterion is expressed as a ratio of allowable moisture in a soil layer to that at field capacity. If the soil moisture on a particular day is above this established criterion, that day is classified as a non-workday and vice versa.[5] Therefore, the soil moisture is the primary factor to determine the degree of tractability used in determining whether field work can be conducted on a particular day (Babeir, Colvin, and Marley 1986; Rotz and Harrigan 2004). However, the selection criterion for tractability is difficult since soil tractability varies from soil to soil, machine to machine, and from one farm operation to another.

Moisture Content of Switchgrass After Cutting

Harvesting of switchgrass is different from that of a grain crop. Figure 1 represents the chains for harvest to conversion of biomass grasses. Figure 1 illustrates that the harvest of switchgrass is not completed by mowing or cutting. Switchgrass is cut by a mower or a mower conditioner (Duffy and Nanhou 2002; Huisman 2003). In some cases they are tedded one or several times, raked into a windrow, and baled with a field baler. In some cases cut grass must be left on the ground for a long period before if can be safely baled. The degree of dryness, that is, moisture content of switchgrass on the ground should be considered prior to baling (Hadders and Olsson 1997).

Baling material with moisture content in excess of 20 percent may result in molding and heating and in some cases, spontaneous combustion. For safe storage it is

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[5] These statements can be expressed as following:

$$\begin{cases} FM < TC \rightarrow \text{Workday} \\ FM \geq TC \rightarrow \text{Non-workday} \end{cases}$$

where FM = fractional available water of top soil layer
TC = tractability coefficient

$$FM = \frac{\text{actual available water of top layer (mm)}}{\text{maximum available water of top layer (mm)}} .$$

generally recommended that the moisture content of cut grasses be no more than 15 percent. Therefore, when moisture content of switchgrass is 15 percent, or less, that day is classified as a workday (McLaughlin et al. 1996; Taliaferro 2005[6]). To rapidly decrease moisture content of cut grass, favorable weather conditions are needed; no rain, low air humidity, and high solar radiation.

Figure 2 includes a flow chart or decision tree that may be used to determine if a particular day is a workday or not a workday. Factors that affect biomass harvest decisions are included.

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[6] Regents Professor Emeritus, Department of Plant and Soil Sciences, Oklahoma State University, Stillwater, Oklahoma.

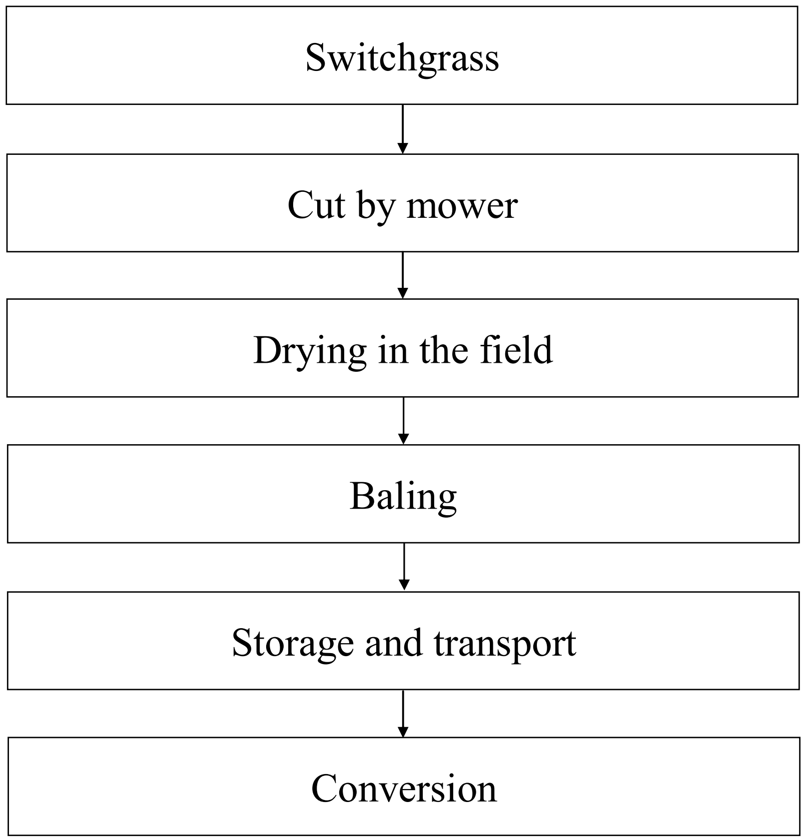

Figure 1. Chain for Harvest to Conversion of Switchgrass

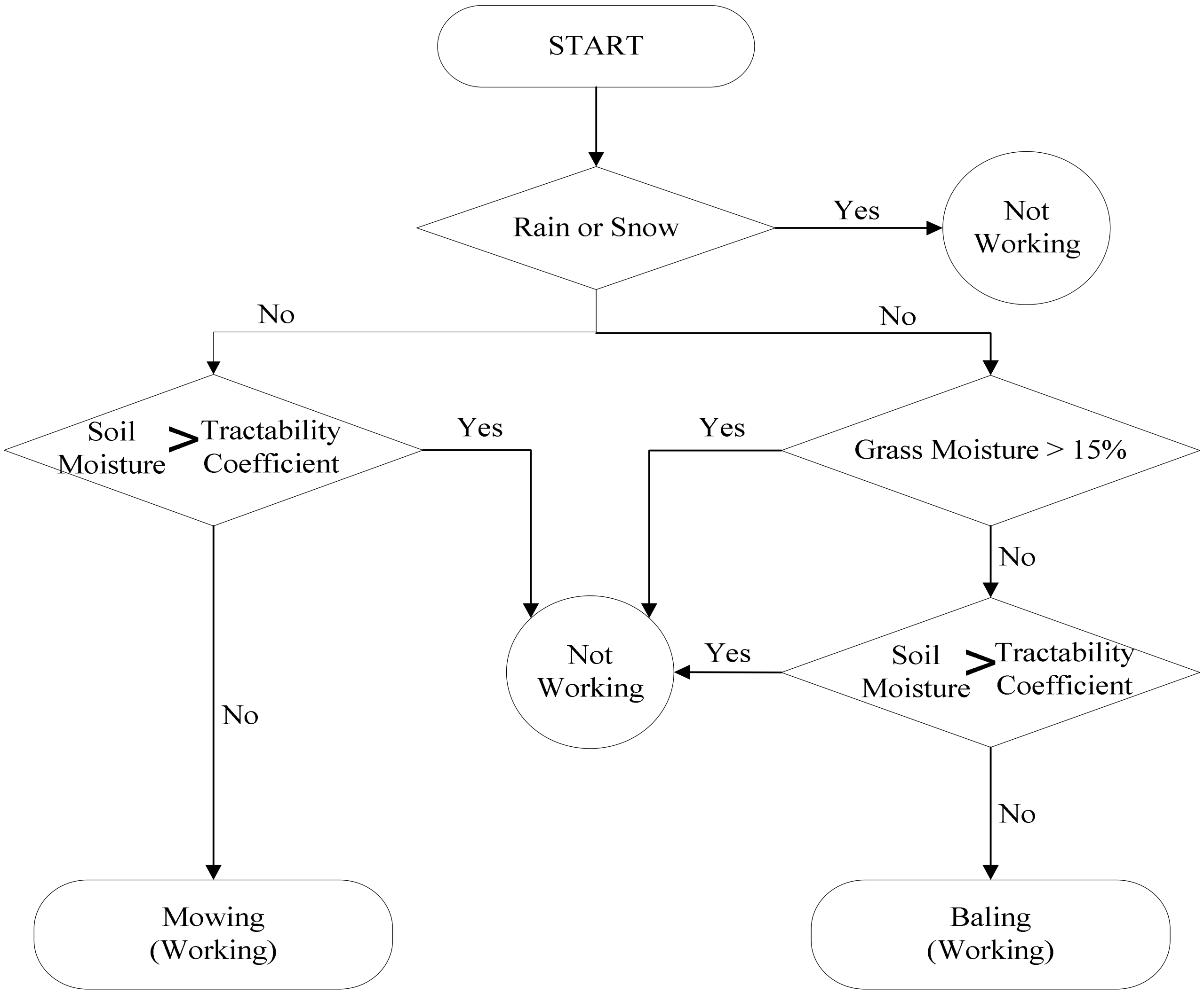

Figure 2. Flow Chart of Making Decision of Workdays

Cost to Deliver Switchgrass Feedstock to Biorefinery

It is anticipated that an efficient switchgrass biorefinery would operate continuously throughout the year and require a flow of feedstock. One alternative for insuring that sufficient feedstock will be available would be for the processing firm to acquire a sufficient quantity of land with long-term leases from land owners and seed the land to a dedicated energy crop such as switchgrass. Alternatively, the firm could engage in long term contracts with farmers to produce a sufficient quantity of feedstock. In either case, the biorefinery would be able to coordinate production, harvest, storage, and transportation of feedstock to fulfill the firm's requirements. The biorefinery may either contract with other firms to harvest and transport the material, or could invest in harvest machines and trucks and manage the total system.

Total cost to deliver feedstock to the biorefinery would significantly affect the overall economics of the business (English, Short, and Heady 1981; Cundiff and Marsh 1996; Epplin 1996; Walsh 1998; Kaylen et al 2000; Sokhansanj and Turhollow 2002; Tembo, Epplin, and Huhnke 2003; Epplin, Mapemba, and Tembo 2005; Petrolia 2006; Leistritz et al. 2006; Tiffany et al. 2006; Mapemba et al. 2007). This cost is influenced by type of feedstock, yield, the number of harvest days during the harvest season, harvest method, storage, storage loss, transportation, feedstock inventory management, biorefinery size, and biorefinery location (Epplin, Mapemba, and Tembo 2005). The major costs may be categorized as feedstock acquisition cost, harvest cost, storage cost, and transportation cost. Figure 3 includes a description of an integrated biorefinery system and illustrates the flow of switchgrass feedstock from fields to a biorefinery.

Figure 3 illustrates a land lease system in which the biorefinery leases land from land owners and establishes switchgrass as a dedicated energy crop. Costs incurred to deliver feedstock would include land lease, switchgrass establishment, fertilizer, storage, harvest, and transportation. The storage costs vary with the quantity of feedstock stored in the field and storage losses. Harvest costs depend upon the harvest window, and number of harvest machines used, which are restricted by the number of workdays during the harvest window. Transportation cost depends upon the distances the material must be shipped from the fields to the processing plant. Also, some of these costs depend upon the size of the biorefinery.

The quantity of feedstock harvested, stored and shipped, acres of land required, number of harvest machines, and location of biorefinery, are all interdependent and ideally would be determined simultaneously. In general, complicated spatial and temporal problems to optimally determine processing plant location and size may be solved with a mathematical programming technique such as Mixed-Integer Linear Programming (MILP). MILP may include either continuous or integer or binary variables. In this study, biorefinery construction and biorefinery location are binary variables and the number of harvest machines is an integer variable.

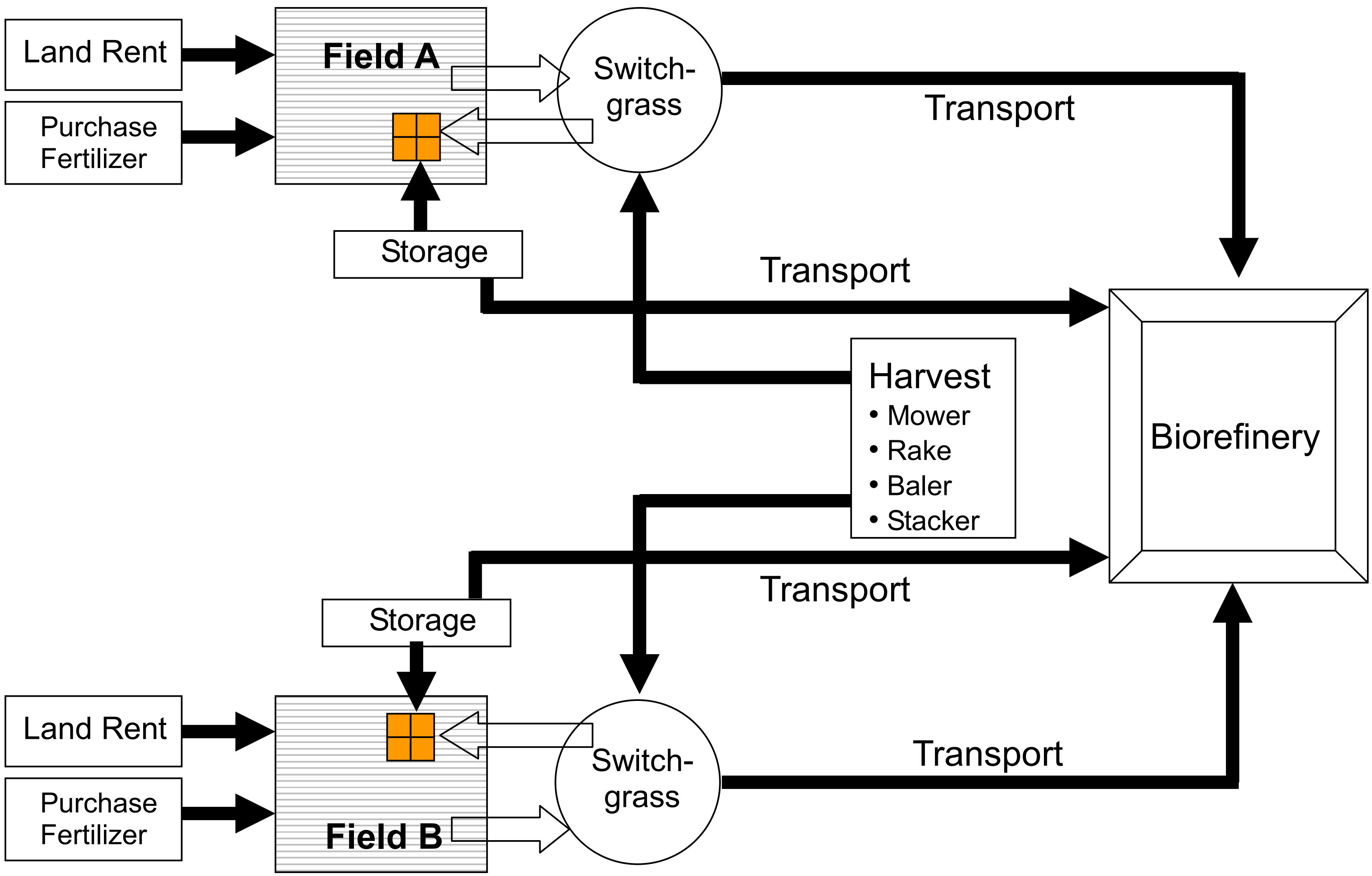

Figure 3. Flow of Switchgrass Feedstock from Fields to a Biorefinery

Types of Feedstock

Corn grain will be the primary feedstock for most ethanol produced for liquid fuel in the U.S. in 2007. As LCB conversion technologies such as enzymatic hydrolysis, gasification, pyrolysis, liquefaction, and anaerobic digestion are developed, LCB could become the primary feedstock for producing fuel ethanol (Mapemba et al. 2007).

An LCB-based system is theoretically far more energy efficient than a corn grain-based system and has the flexibility to use a variety of feedstocks. A variety of feedstocks includes crop residues such as wheat straw and corn stover, native perennial grasses such as bermudagrass and tall fescue, and dedicated energy crops such as switchgrass.

Among the various LCB feedstocks, switchgrass has been regarded as a suitable energy crop based on the evaluation of yield potential, environmental attributes, and possible economic returns to land owners (Lewandowski et al. 2003; McLaughlin and Kszos 2005.; Jensen et al. 2006; Busby et al. 2007; Monti et al. 2007). Switchgrass (*Panicum virgatum*) is a native species of the Great Plains and grows throughout much of the southern and southeastern United States. Switchgrass is well-adapted to grow in a large portion of the United States with low fertilizer applications and high resistance to naturally occurring pests and diseases. In addition, switchgrass only needs to be planted once every ten years or more, but can be harvested annually using conventional hay harvest equipment (e.g. mowers, rakes, balers). Harvesting can be performed in either a two harvest system or a single harvest occurring after first frost. Some Conservation Reserve Program (CRP) acres include grasses and by policy could be harvested once in three years (Mapemba et al. 2007).

CHAPTER IV

PROCEDURES AND DATA

Soil Water Balance Model

To estimate the number of available field workdays during the period of harvest for warm-season perennial grasses, information is needed to determine daily fluctuation of soil moisture content. A field water balance model can be used to predict soil moisture content. The general equation describing the water balance from the soil surface to the soil profile zone is given by (Tindall and Kunkel 1999; Peters 2003; Jury and Horton 2004):

$$\Delta SW = P + I + LF_{in} - R - ET - D - LF_{out} , \tag{4.1}$$

where ΔSW is the periodic change in total soil water content in mm, P is the precipitation in mm, I is irrigation in mm, LF_{in} is lateral movement of water in the soil profile in mm, R is surface runoff in mm, ET is actual evapotranspiration in mm, D is drainage or deep percolation below the soil profile in mm, and LF_{out} is lateral flow out of the soil profile in mm.

For our purposes, LF_{in} and LF_{out} are considered negligible. Likewise, irrigation is not considered because use of irrigation for production of switchgrass in Oklahoma is not anticipated. ΔSW is the difference in the soil between current period and one period before the current period, $\Delta SW = SW_t - SW_{t-1}$. Therefore, soil moisture content in a soil profile at the current time is represented by:

(4.2) $$SW_t = SW_{t-1} + P - R - ET - D.$$

Precipitation

Rainfall is the only source of water to the soil profile. The total amount and the intensity of rainfall greatly influence the amount of water entering the soil. Because movement of water into the soil profile takes time, more water will be absorbed from lower intensity rainfalls. High intensity rainfall exceeding the infiltration rate results in surface runoff. The amount of water entering the soil is also affected by the soil moisture status of the soil (Bargen, Meng, and Schroeder 1986, p. 4).

Surface Runoff

Runoff is the portion of the precipitation that makes its way toward stream channels, lakes, or oceans as surface or subsurface flow. The term "runoff" usually means surface flow. In general, runoff will occur only when the rate of precipitation exceeds the rate at which water may infiltrate into the soil. After the infiltration rate is satisfied, water begins to fill the depressions, small and large, on the soil surface (Schwab et al. 1993, p.68). In this study, surface runoff is estimated using the SCS Runoff Curve Number (CN) method developed by U.S. Soil Conservation Service (SCS) in 1972. The SCS runoff equation is:

(4.3) $$R = \frac{(P - 0.2S)^2}{(P + 0.8S)} \quad \text{for} \quad P \geq 0.2S,$$

where R is runoff in mm, P is the precipitation in mm, and S is a retention parameter.

Since precipitation must satisfy the demands of evapotranspiration, intercept, infiltration, surface storage, surface detention, and channel detention, before runoff occurs, 0.2S is the initial abstraction from the rainfall (SCS 1986; Schwab et al. 1993). S is given by:

(4.4) $$S = \frac{25400}{CN} - 254.$$

The runoff curve number (CN), which depends on soil characteristics, vegetative-cover, and hydrological conditions, is provided by SCS (1986). More than 4,000 soils have been classified by the SCS (1986) into four hydrological soil groups. The four hydrologic soil groups are classified as A, B, C, and D. The classification of all four soil groups and run-off curve number are given in Table 4 through Table 6.

Evapotranspiration

Evaporation is the transfer of liquid water into the atmosphere. The water molecules, both in the air and in the water, are in rapid motion. Evaporation occurs when the number of moving molecules that break from the water surface and escape into the air as vapor is larger than the number that reenters the water surface from the air and become entrapped in the liquid. Transpiration is the process through which water vapor passes into the atmosphere through the tissues of living plants. In areas of growing plants, water passes into the atmosphere by evaporation from soil surfaces and by transpiration from plants. For convenience in analyzing water transfer in this common situation, the two are

Table 4. Soil Groups Used to Estimate the Runoff Curve Number

Soil Group	Description	Soil texture
A	Soils have low runoff potential and high infiltration rates even when thoroughly wetted. They consist chiefly of deep, well to excessively drained sand or gravel and have a high rate of water transmission (greater than 0.30 in/hr)	Sand, loamy sand, or sandy loam
B	Soils have moderate infiltration rates when thoroughly wetted and consist chiefly of moderately deep to deep, moderately well to well drained soils with moderately fine to moderately coarse textures. These soils have a moderate rate of water transmission (0.15-0.30 in/hr)	Silt loam or loam
C	Soils have low infiltration rates when thoroughly wetted and consist chiefly of soils with a layer that impedes downward movement of water and soils with moderately fine texture. These soils have a low rate of water transmission (0.05-0.15 in/hr)	Sandy clay loam
D	Soils have high runoff potential. They have very low infiltration rates when thoroughly wetted and consist chiefly of clay soils with a high swelling potential, soils with a permanent high water table, soils with a claypan or clay layer at or near the surface, and shallow soils over nearly impervious materal. These soils have a very low rate of water transmission (0-0.05in/hr)	Clay loam, silty clay loam, sandy clay, silty clay, or clay

Source: U.S. SCS (1986)

Table 5. Hydrologic Soil Group (HSG) for Oklahoma

County	HSG	County	HSG	County	HSG
Adair	C	Grant	N/A	Nowata	B
Alfalfa	N/A	Greer	N/A	Okfuskee	N/A
Atoka	C	Harmon	N/A	Oklahoma	N/A
Beaver	N/A	Harper	D	Okmulgee	N/A
Beckham	B	Haskell	N/A	Osage	D
Blaine	N/A	Hughes	B	Ottawa	N/A
Bryan	N/A	Jackson	N/A	Pawnee	N/A
Caddo	D	Jefferson	N/A	Payne	C
Canadian	B	Johnston	B	Pittsburg	N/A
Carter	D	Kay	N/A	Pontotoc	B
Cherokee	D	Kingfisher	B	Pottawatomie	C
Choctaw	N/A	Kiowa	N/A	Pushmataha	C
Cimarron	N/A	Latimer	D	Rogers	N/A
Cleveland	C	Le Flore	N/A	Seminole	D
Coal	N/A	Lincoln	N/A	Sequoyah	N/A
Comanche	N/A	Logan	N/A	Stephens	N/A
Cotton	C	Love	N/A	Texas	N/A
Craig	B	Major	N/A	Tillman	D
Creek	N/A	Marshall	N/A	Tulsa	N/A
Custer	C/D	Mayes	D	Wagoner	N/A
Delaware	B	McClain	N/A	Washington	C
Dewey	B	McCurtain	N/A	Washita	N/A
Ellis	D	Mclntosh	N/A	Woods	D
Garfield	N/A	Murray	B	Woodward	B
Garvin	D	Muskogee	C		
Grady	N/A	Noble	B		

Note: N/A is “Not available”.
Source: U.S. SCS (1986)

Table 6. Runoff Curve Number for Hydrologic Soil-Cover Complexes

Cover type		Hydrologic Condition	Curve numbers for Hydrologic Soil Group			
			A	B	C	D
Pasture, grassland, or range-continuous forage for grazing		Poor[a]	68	79	86	89
		Fair[b]	49	69	79	84
		Good[c]	39	61	74	80
Meadow-continuous grass, protected from grazing and generally mowed for hay		—	30	58	71	78
Brush-weed-grass mixture with brush the major element		Poor[d]	48	67	77	83
		Fair[e]	35	56	70	77
		Good[f]	30	48	65	73
Fallow	Bare soil	—	77	86	91	94
	Crop residue cover (CR)	Poor[g]	76	85	90	93
		Good[h]	74	83	88	90
Row Crop	Straight row (SR)	Poor	72	81	88	91
		Good	67	78	85	89
	SR+CR	Poor	71	80	87	90
		Good	64	75	82	85
	Contoured (C)	Poor	70	79	84	88
		Good	65	75	82	86
	C+CR	Poor	69	78	83	87
		Good	64	74	81	85
	C & terraced (C&T)	Poor	66	74	80	82
		Good	62	71	78	81
	C&T+CR	Poor	65	73	79	81
		Good	61	70	77	80
Small Grain	SR	Poor	65	76	84	88
		Good	63	75	83	87
	SR+CR	Poor	64	75	83	86
		Good	60	72	80	84
	C	Poor	63	74	82	85
		Good	61	73	81	84
	C+CR	Poor	62	73	81	84
		Good	60	72	80	83
	C&T	Poor	61	72	79	82
		Good	59	70	78	81
	C&T+CR	Poor	60	71	78	81
		Good	58	69	77	80
Close-seeded or broadcast legumes or rotation meadow	SR	Poor	66	77	85	89
		Good	58	72	81	85
	C	Poor	64	75	83	85
		Good	55	69	78	83
	C&T	Poor	63	73	80	83
		Good	51	67	76	80

[a] Poor: <50% ground cover or heavily grazed with no mulch.
[b] 50 to 75% ground cover and not heavily grazed.
[c] Good: >75% ground cover and lightly or only occasionally grazed.
[d] Poor: <50% ground cover.
[e] Fair: 50 to 75% ground cover.
[f] Good: >75% ground cover.
[g] Poor: Factors impair infiltration and tend to increase runoff.
[h] Good: Factors encourage average and better than average infiltration and tend to decrease runoff.

Source: U.S. SCS (1986)

combined and referred to as evapotranspiration (Schwab et al. 1993, pp. 53-54).

Since evaporation and transpiration occur simultaneously, there is no easy way of distinguishing between the two processes. Apart from the water availability in the topsoil, the evaporation from a cropped soil is mainly determined by the fraction of the solar radiation reaching the soil surface. This fraction decreases over the growing period as the crop develops and the crop canopy shades more and more of the ground area. When the crop is small, water is predominately lost by soil evaporation, but once the crop is well developed and completely covers the soil, transpiration becomes the main process (Allen et al. 1998, p. 3).

Thus, actual evapotranspiration varies across crop type and crop growth stages. Figure 4 illustrates differences in evapotranspiration during the various growth stages. Actual evapotranspiration is given by (Jensen, Burman, and Allen 1990; Burman and Poochop 1994; Allen et al. 1998; Hunsaker, Pinter, and Kimball 2005; Kato and Kamichika 2006):

(4.5) $$ET = K_{c,t} ET_o$$

where $K_{c,t}$ is a crop coefficient at the period of t and ET_o is a standardized reference or potential evapotranspiration in mm per day.

<u>Drainage</u>

Drainage is the amount of water that passes below the root zone of crops. Dyer and Baier (1979) assumed that drainage of water above field capacity did not occur instantaneously. That is, after rain, drainage of gravity water is not immediate but takes

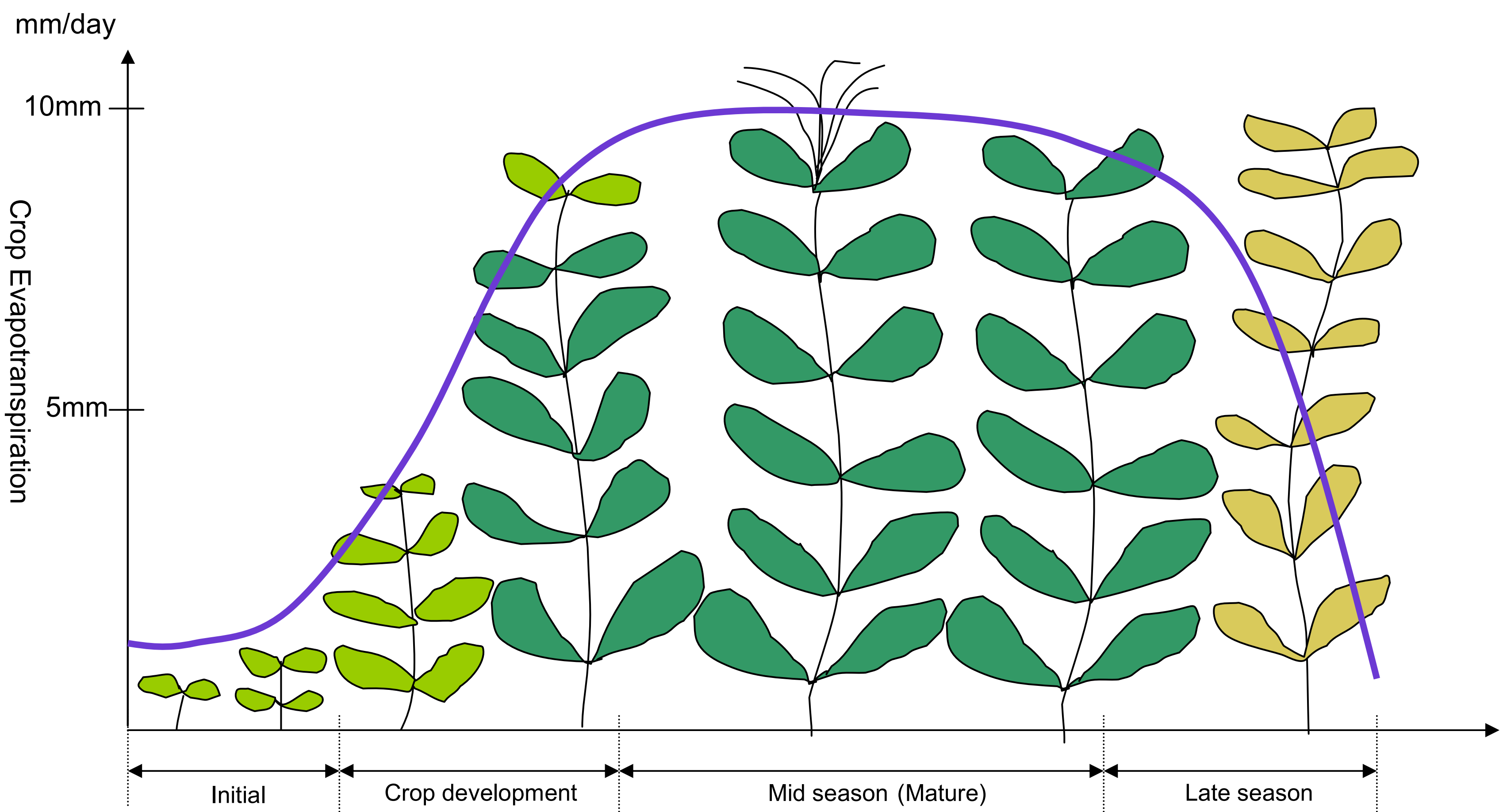

Figure 4. Variations of Evapotranspiration over the Growing Period

Source: Allen et al. (1998)

place over one or more days. This effect was simulated by allowing only a certain percentage of the gravity water in a certain soil profile zone to drain out each day. Gravity water drainage from the soil layer was computed by (Dyer and Baier 1979; Babeir, Colvin, and Marley 1986; Allen et al. 1998):

$$D_t = DRS\left[(P_t - R_t) - D_{r,t-1}\right] \geq 0 \qquad (4.6)$$

where DRS is a drainage coefficient between zero an one, P_t is the precipitation at *t* time, R_t is the surface runoff at *t* time, and $D_{r,t-1}$ is the depletion at *t-1* time.

A soil water balance spreadsheet was used to compute daily moisture content of soil. This spreadsheet was modified from the original spreadsheet (called FAO-56 spreadsheet) developed by Allen et al. (1998) and published in the Food and Agriculture Organization Paper No. 56 (FAO-56). The FAO-56 spreadsheet was originally developed for calculating reference and crop evapotranspiration from meteorological data and crop coefficients based on growth stages of crop. This study modified the FAO-56 spreadsheet to calculate soil moisture content and determine a workday in a certain day. The equations and coefficients for reference and crop evapotranspiration used in the FAO-56 spreadsheet are described in Appendix A.

Drying of Cut Grasses Model

Figure 5 illustrates how the moisture content of cut grasses changes over time in the field. During the day under favorable weather conditions such as sunshine, grasses lose moisture by diffusion and evaporation into the atmosphere. On the other hand, moisture content of cut grasses increases during the night because of no sunlight, low temperature, and high humidity. Cut grass must be left on the ground until the moisture content decreases below the threshold level (e.g. 15%) and then cut grass can be safely baled.

Factors That Affect Drying

Field drying is influenced by conditioning treatments, swath structure, and weather conditions. The width of the swath and the resulting swath density are important factors. When the cut grasses are spread over more of the field surface, they are exposed more to the drying air and radiant solar energy and thus dry more rapidly. On the other hand, although the environment is ideal for drying, the drying rate may be relatively low when cut grass is piled into a relatively narrow swath.

Among weather parameters, solar radiation is the factor with the greatest influence on drying rate. On a very sunny day, cut grasses can dry very quickly. Vapor pressure deficit is another important weather parameter. Vapor pressure deficit is a combined measure of air temperature and humidity. If the humidity is low and air temperature is high, then the vapor pressure deficit is high. A high vapor pressure deficit value indicates a warm and dry day and under these conditions substantial moisture

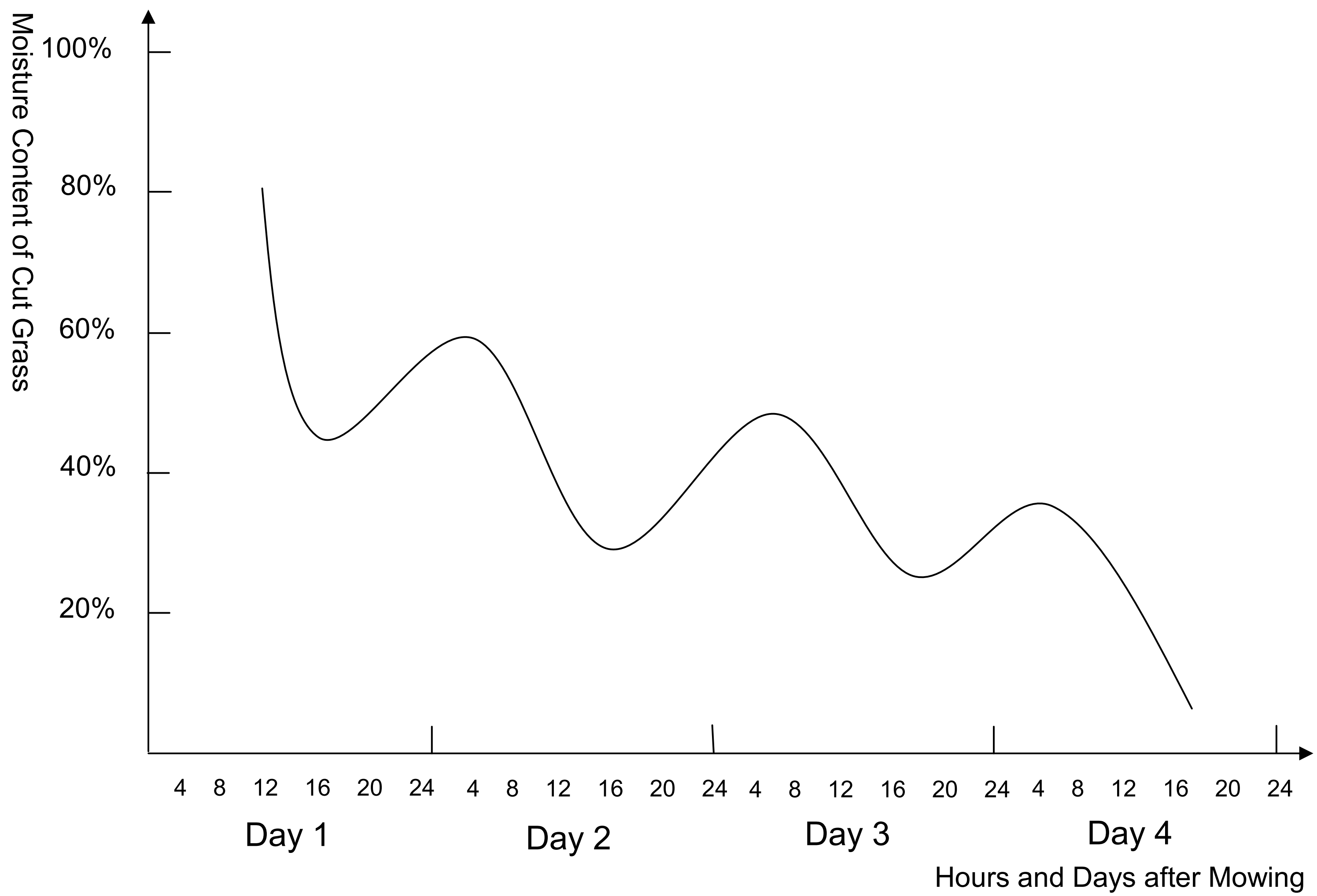

Figure 5. Drying Curve of Cut Grass

Source: Savoie et al. (1982)

moves from cut grass to the atmosphere.

Soil moisture also influences drying because the cut grasses are spread over the soil surface. Wet soil restrains the drying of the swath bottom, and it may prevent the cut grasses from drying completely. However, unless the soil is very wet, this factor's influence is relatively small.

Another factor is the time elapsed after mowing. Cut grasses dry faster on mowing day than on subsequent days. Immediately following mowing, the moisture is uniformly spread throughout the swath. Moisture near the surface of the swath can readily evaporate into the surrounding air. As the swath dries, the moisture must move to the surface from within the swath which slows drying.

Conditioning treatments also influence the field drying rate. There are two harvest options: no conditioning and standard mechanical conditioning. Standard conditioning includes mechanical crushing of the cut grasses with intermeshing rubber rolls. The use of standard mechanical conditioning increases the rate of drying (Rotz 1985; Rotz and Chen 1985).

Drying Model

This study employs the drying model developed by Rotz and Chen (1985) to calculate the field drying rate of cut grasses. Rotz and Chen (1985) originally developed their model to find a field drying rate for alfalfa. Later they adapted the model to determine the field drying rate of cut grasses (Rotz and Coiner 2005). Drying rate for cut grasses using standard mechanical conditioning is modeled as a function of the environment, swath density, and the application rate of chemical conditioning treatment. The drying model developed by Rotz and Chen (1985) is:

(4.7) $$DR = \frac{SI(1+9.03)+43.8(VPD)}{2767+61.4(SM)+(SD)(1.82-0.83(DAY))(1.68+24.8(AR))}$$

where:

DR = drying rate constant per hour

SI = Solar insolation, W/m^2 (W = watts)

VPD = vapor pressure deficit, kPa

SM = soil moisture content, % dry basis

SD = swath density, g/m^2

DAY = 1 for the first day, 0 otherwise

AR = application rate of chemical solution, solution in grams / dry-matter in grams.

However; since a chemical conditioning treatment is not anticipated for cut grasses, AR could be set to zero. Then, the modified model should be:

(4.8) $$DR = \frac{SI+43.8(VPD)}{2767+61.4(SM)+1.68(SD)(1.82-0.83(DAY))}.$$

The change in moisture content of the cut grasses across each period of the day is described as an exponential function of the moisture ratio, the drying rate, and time.

(4.9) $$\frac{M_{d,n}-M_{e,n}}{M_{o,n}-M_{e,n}} = e^{-DR(T)}$$

where:

$M_{d,n}$ = moisture content (dry basis) of day time at the end of time T on the nth day after cutting

$M_{e,n}$ = equilibrium moisture content (dry basis) on the n^{th} day after cutting

$M_{o,n}$ = moisture content (dry basis) at the beginning of time T on the n^{th} day after cutting

T= length of drying period, h.

Assuming equilibrium moisture content ($M_{e,n}$) is zero,

(4.10) $$M_{d,n} = M_{o,n} e^{-DR(T)}$$

Another important consideration in the field drying process is the amount of rewetting that occurs. Models for dew and rain absorption were developed through consideration of moisture absorption theory (Rotz 1985). Dew was assumed to be absorbed into cut grass following an exponential function of the moisture ratio, swath density and time.

(4.11) $$M_{f,n} = M_{e,n} + (M_{i,n} - M_{e,n}) \exp(-(T)(WR)/(SD))$$

where:

$M_{f,n}$ = moisture content (dry basis) at the end of night time (i.e. at sunrise) on the n^{th} day after cutting

$M_{e,n}$ = equilibrium moisture content (dry basis) in the night environment on the n^{th} day after cutting

$M_{i,n}$ = moisture content (dry basis) at the beginning of night (i.e. at sunset) on the n^{th} day after cutting (= $M_{d,n}$)

T = length of night period, h

WR = dew moisture absorption rate of cut grass = 4.0 g/m^2 per hour.

SD = swath density, g/m^2.

The equilibrium moisture was modeled as an exponential function of relative humidity and wind (Rotz 1985).

(4.12) $$M_{e,n} = e^{-2.5(1-RH_n)}\left(0.4 + 3.6e^{-0.2(WIND_n)}\right)$$

where:

RH = average relative humidity over night on the n^{th} day after cutting, fraction

WIND = average wind speed at 2m over night on the n^{th} day after cutting, m/s.

To model rewetting through rain absorption, a form of equation (4.13) was used. In this case, the equilibrium moisture content was fixed at a value of 4. Since the duration of the wetting period was not known, it was assumed to be proportional to the amount of rainfall. The following model was obtained (Rotz 1985):

(4.13) $$M_{r,n} = 4.0 + (M_{o,n} - 4.0)\exp(-WR(RF_n)/SD)$$

where:

$M_{r,n}$ = moisture content following rain on the n^{th} day after cutting

WR = moisture absorption rate of cut grass = 150 g/m^2 per mm

RF = rainfall on the n^{th} day after cutting, mm.

The following procedures represent an outline of computing the moisture content of cut grasses illustrated in Figure 5 using equation (4.8) through (4.13).

Step 1: Compute the moisture content during the day time (e.g. 12 hours) on cutting day using equations (4.8) and (4.10).

The moisture content of cut grass at the end of time T on cutting day is assumed to be $M_{d,0}$. If $M_{d,0}$ is greater than 15%, then go to the step 2.

Step 2: Compute the moisture content during the night time (e.g. 12 hours) on cutting day using equations (4.11) and (4.12). Hence, moisture content of cut grass during the night time is:

$$M_{f,0} = M_{e,0} + (M_{d,0} - M_{e,0})\exp(-(T)(WR)/(SD)).$$

Step 3: Compute the moisture content during the day time on the first day after cutting day using equations (4.8) and (4.10) as below:

$$M_{d,1} = M_{f,0}e^{-DR(T)}.$$

If it rains during the day, then compute the moisture content using equation (4.13) instead of equations (4.8) and (4.10)

Step 4: If $M_{d,1}$ is greater then 15%, then compute the moisture content during the night time on the first day using equations (4.11) and (4.12) as below:

$$M_{f,1} = M_{e,1} + (M_{d,1} - M_{e,1})\exp(-(T)(WR)/(SD))$$

Step 5: Compute the moisture content during the day time on the second day after cutting day using equations (4.8) and (4.10) as below:

$$M_{d,2} = M_{f,1}e^{-DR(T)}.$$

Step 6: If $M_{d,2}$ is equal to or less then 15%, then stop these procedures. If $M_{d,2}$ is greater then 15%, compute the moisture content during the night time on the second day.

Probability Distribution Model

Empirical cumulative probability distributions functions (empirical CDF) are used to determine the probability distribution of the number of suitable field workdays for each month. The empirical CDF is the proportion of observations and is based on sample $Y_1, \ldots, Y_n$ as a step function represented as follows (SAS):

$$F_n(y) = \frac{\text{number of observation in the sample} \leq y}{n} = \frac{1}{n}\sum_{i=1}^{n} I(Y_i \leq y) \tag{4.14}$$

where:

n = number of observations

$I(Y_i \leq y)$ = indicator function with value 1 if $Y_i \leq y$ and with value 0 otherwise

Y_i = value of indicator for the i^{th} observation

y = indicator level of interest.

An empirical CDF can be constructed from the sequences of "workday" and "non-workday". First, for each time period (e.g. month) in each year, the numbers of workdays are summed. The sums form observations of the number of field workdays in each time period. For example, the numbers of workdays in July are 25, 23, 27, and 20 in 1994, 1995, 1996, and 1997, respectively. Second, the observations were arranged from smallest to largest. Finally, a discrete empirical CDF is constructed using equation (4.14) (Rosenberg et al. 1982).

The Mixed Integer Mathematical Programming Model

One of the specific objectives of this study is to determine the optimal number of harvest machines for a biorefinery located in Oklahoma and the consequences in terms of dollars to deliver a ton of switchgrass for different levels of probability of completing harvest in the available time. In this study, a mixed integer mathematical programming model developed by Tembo (2000) and Mapemba (2005) was used to complete this objective. In this model, based on the maximization of net present worth over all biorefineries, optimal size and location of biorefineries for Oklahoma are determined.

A major difference between Mapemba's and Tembo's model is that Mapemba (2005) designed a harvest unit as an integer and endogenously chosen activity.[7] Mapemba (2005) used the coordinated set of harvest machines designed by Thorsell (2004) as a harvest unit. Thorsell's harvest unit consists of three mowers, three rakes, three balers, a bale transporter, nine tractors, and ten laborers. Mapemba (2005) assumed that the number of workdays by month suitable for mowing and those suitable for baling are the same. The current study extends this work by recognizing that the number of days suitable for baling in most months is less than the number of days suitable for mowing. The Mapemba version of the Tembo model is extended by including separate estimates of days suitable for mowing and days suitable for baling for each month. The model is further extended by incorporating separate mowing unit integer activities and separate raking-baling-stacking unit integer activities.

In this section, a full description of the model is presented. Descriptions of all the indices, parameters and variables used in this model are also summarized in Appendix B. A mathematical description of the integrative investment appraisal biorefinery location, switchgrass production, storage, and transportation optimization model is:

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[7] Tembo (2000) determined economical source of LCB, timing of harvest and storage, inventory management, biorefinery size, biorefinery location, and breakeven price of ethanol for a gasification-fermentation process in Oklahoma using a multi-region, multi-period, mixed integer mathematical programming. He used a fixed harvest cost per acre, and reported that harvest costs constituted 8% of the total cost to produce a gallon of ethanol. Even though he 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 (Mapemba 2005, p.19).

$$\max_{q,x,xt,xs,A} NPW = \left\{ \sum_{m=1}^{M} \left[\sum_{j=1}^{J}\sum_{s=1}^{S}\sum_{g=1}^{G} \rho_g q_{jsgm} - \sum_{i=1}^{I}\sum_{f=1}^{F} \alpha_k A_{ikm} - \sum_{i=1}^{I} \gamma \cdot xsp_{im} - \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{s=1}^{S} \tau_{ij} xt_{ijsm} \right] - \sum_{j=1}^{J}\sum_{s=1}^{S}\sum_{ft=1}^{FT} TAFC_{s,ft}\beta_{js} - \omega HUM - \varpi HUB \right\} \times PVAF \tag{4.15}$$

where *NPW* is the net present worth of the industry, *q* is quantity of output such as ethanol and by-products (e.g. CO_2, N_2 and ash), *A* is the number of acres of switchgrass harvested, *xsp* is tons of switchgrass stored in the field, and *xt* is tons of switchgrass transported from the production counties to biorefinery location. β is a binary variable (0,1), equal to one if a biorefinery of size *s* is optimum at location *j* and zero otherwise. *HUM* and *HUB* are integer variables associated with the total number of harvest units for mowing and harvest units for raking-baling-stacking, respectively.

M, J, S, G, I, F, and *FT* represent index variables; *m* is a set of months and *j* is a set of counties in which a biorefinery may be potentially located, *s* is a set of biorefinery sizes, *g* is a set of products, *i* is a set of switchgrass production regions, *f* is a set of level of fertilizer applied, and *ft* is a set of types of facilities.

$\rho, \alpha, \gamma, \tau, \psi, \omega, \varpi,$ *TAFC* and *PVAF* represent parameters; ρ is a unit price of outputs, α is a cost of producing switchgrass on leased land, γ is a cost of storing a ton of switchgrass in the field, τ is a cost of transporting a ton of switchgrass from a production region to a biorefinery, ω is the annual cost of a harvest unit for mowing switchgrass, ϖ is the annual cost of a harvest unit for raking-baling-stacking switchgrass, *TAFC* is the amortized annual cost of constructing and operating a biorefinery, and *PVAF* is the present value of annuity factor, which is given as $PVAF = {(1+r)^T - 1}\big/{r(1+r)^T}$, where T is useful biorefinery life in years, and r is the discount factor.

To determine a more precise estimate of the number of harvest units required to harvest and deliver a flow of feedstock to biorefineries, constraints used in Mapemba's model were employed and modified. Mapemba's model was augmented with added constraints that were necessary to enable separation of mowing operations from raking-baling-stacking operations.

The definition and description of the model constraints draw heavily from Mapemba (2005, pp. 68~72). Equation (4.16) constrains harvested acres to not exceed the number of acres in each county that can be harvested for switchgrass.

(4.16) $$\sum_{f=1}^{F}\sum_{m=1}^{M} A_{ifm} - \sum_{l=1}^{L} BP_i LAND_i \leq 0, \quad \forall i.$$

where $LAND$ is total acres of land available for producing switchgrass, BP ($0 \leq BP \leq 1$) is the proportion of available land that can be harvested for switchgrass.

Equation (4.17) states that switchgrass harvested is equal to the available switchgrass in the field less any field losses. In other words, this constraint computes how much switchgrass can be produced from harvestable acres.

(4.17) $$\sum_{f=1}^{F} x_{ifm} - YAD_m \sum_{f=1}^{F} A_{ifm} BYLD_{if} = 0, \quad \forall i, m.$$

where x is tons of switchgrass harvested, $BYLD$ is a potential yield of switchgrass (dry tons per acre), and YAD is a yield adjustment factor ($0 \leq YAD \leq 1$), which is based on the assumption that switchgrass yields are highest if harvested at certain times of the year and decline thereafter. Thus, *YAD* has variations by month of harvest and *YAD* being equal to one means that switchgrass yield is highest and vice versa.

Equation (4.18) ensures that no acres can be harvested in months when the yield adjustment factor is equal to zero.

$$(4.18) \qquad \sum_{f=1}^{F} A_{ifm} = 0 \quad \text{if } YAD_m = 0, \quad \forall i, m.$$

Equation (4.19) states that in each month and at each source, the sum of switchgrass transported to biorefineries and switchgrass put in storage, switchgrass should equal the sum of current production and usable portion of stored switchgrass.

$$(4.19) \qquad \sum_{j=1}^{J}\sum_{s=1}^{S} xt_{ijsm} + xs_{im} - \theta_i xs_{im-1} - \sum_{f=1}^{F} x_{ifm} = 0, \quad \forall i, m.$$

where the parameter θ_i is the proportion of switchgrass which is usable following one month of in-field storage at production region *i* and is computed as $\theta_i = 1 - dt_i$, where dt_i is monthly deterioration rate for switchgrass when stored at production region *i*.

Equation (4.20) ensures that quantity of switchgrass shipped from production regions to biorefineries is equivalent to total switchgrass harvested excluding in-field storage losses.

$$(4.20) \qquad \sum_{f=1}^{F}\sum_{m=1}^{M} x_{ifm} - \sum_{j=1}^{J}\sum_{s=1}^{S}\sum_{m=1}^{M} xt_{ijsm} - (1-\theta_i)\sum_{m=1}^{M} xs_{im} = 0, \quad \forall i.$$

Equation (4.21) states that, in each month, the quantity of switchgrass harvested plus that quantity removed from storage must equal the quantity of switchgrass transported from switchgrass producing counties to biorefineries plus quantity placed in storage. In other words the equation says total supply should equal total demand.

(4.21) $$\sum_{i=1}^{I}(x_{im}+xsn_{im})-\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{s=1}^{S}xt_{ijsm}-\sum_{i=1}^{I}xsp_{im}=0, \quad \forall m.$$

where *xsn* is the quantity of switchgrass removed from storage and *xsp* is the quantity of switchgrass in a certain month and stored in a certain place.

Equations (4.22) and (4.23) state that the sum of harvest units for mowing and harvest units for raking-baling-stacking used in each month may not exceed the total number of harvest units for mowing and harvest units for raking-baling-stacking endogenously determined by the model, respectively.

(4.22) $$\sum_{i=1}^{I}xhum_{im}-HUM\le 0, \quad \forall m.$$

(4.23) $$\sum_{i=1}^{I}xhub_{im}-HUB\le 0, \quad \forall m.$$

where *xhum* and *xhub* are the harvest units for mowing and the harvest units for raking-baling-stacking used in each month, respectively.

Equations (4.24) and (4.25), state that, in each switchgrass producing county and month, the quantity of switchgrass harvested may not exceed the combined harvesting capacity of the number of harvest units for mowing and raking-baling-stacking determined by the model, respectively.

(4.24) $$x_{im}-xhum_{im}CAPHUM_{im}\le 0 \quad \forall i,m.$$

(4.25) $$x_{im}-xhub_{im}CAPHUB_{im}\le 0 \quad \forall i,m.$$

where *CAPHUM* and *CAPHUB* are the capacity of a single harvest unit for mowing switchgrass and raking-baling-stacking switchgrass in each month, respectively.

Equation (4.26) ensures a proper sequence of operations for mowing and raking-baling-stacking. Hence, raking-baling-stacking operations in a particular switchgrass producing county and month must not be performed prior to the mowing operation in the same county and month.

(4.26) $$xhum_{im}CAPHUM_{im} - xhub_{im}CAPHUB_{im} = 0 \quad \forall i, m.$$

Equation (4.27) links switchgrass processing capacity at the biorefinery 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 biorefinery in that month will be bounded by $0 \le q_{jsem} \le CAPP_s$. If $\beta_{js} = 0$, expression $CAPP_s\beta_{js}$ will also equal to zero and since q_{jsem} cannot assume a negative value, then it must also equal zero.

(4.27) $$q_{jsem} - CAPP_s\beta_{js} \le 0, \quad \forall j, s, m.$$

where *CAPP* is the biorefinery capacity associated with the biorefinery size.

Equation (4.28) links switchgrass storage capacity at the biorefinery to the binary variable. If $CAPS_s\beta_{js} = CAPS_s$, the total switchgrass storage at any biorefinery will be bounded by $0 \le xs_{jm} \le CAPS_s$. If $\beta_{js} = 0$, expression $CAPS_s\beta_{js}$ will also equal to zero and since x_{jm} cannot assume negative value, then it must also equal zero. No storage upper bounds are assumed for in-field storage.

(4.28) $$xs_{jm} - CAPS_s\beta_{js} \le 0, \quad \forall j, s, m.$$

where *CAPS* is the switchgrass storage facility capacity associated with biorefinery size.

Equation (4.29) imposes that total switchgrass processed or stored at the biorefinery may not exceed the total switchgrass supply.

(4.29) $$\sum_{i=1}^{I} xt_{ijsm} + \phi_j xs_{jm-1} - xs_{jm} - xp_{jsm} = 0, \quad \forall j, m, s.$$

where *xp* the quantity of switchgrass processed by a biorefinery and ϕ is the proportion of switchgrass stored at the biorefinery that is usable a month later.

Equation (4.30) balances total switchgrass delivered to the biorefineries with the sum of processed switchgrass and on-site storage losses.

(4.30) $$\sum_{i=1}^{I}\sum_{m=1}^{M} xt_{ijsm} - (1-\phi_j)\sum_{m=1}^{M} xs_{jsm} - \sum_{m=1}^{M} xp_{jsm} = 0, \quad \forall j,s.$$

Equation (4.31) allows imposition of a minimum switchgrass inventory at the biorefinery to avoid switchgrass supply interruptions that may occur during any of the periods.

(4.31) $$xs_{jm} - MBINV_s \beta_{js} \geq 0, \quad \forall j,m,s.$$

where *MBINV* is minimum switchgrass inventory at the biorefinery.

Equation (4.32) imposes a Leontief production function (fixed input-output coefficients) at the biorefinery. The quantity of each output produced is directly equal to the product of the corresponding transformation coefficient, λ, and quantity of switchgrass used, *xp*. The inequality allows for production losses.

(4.32) $$q_{jsgm} - \lambda_g xp_{jsm} \leq 0, \quad \forall g,j,m,s.$$

Equation (4.33) imposes a Leontief production possibilities frontier between the bio-product and each by-product.

(4.33) $$q_{jsem}\lambda_g - q_{jsgm}\lambda_e = 0, \quad \forall g,j,m,s.$$

Equation (4.34) represents an upper bound on the number of biorefineries that can be built, assumed here to be equal to one. If a particular biorefinery is too small this constraint will force the model to construct a larger biorefinery other than construct several smaller-sized biorefineries at one location.

(4.34) $$\sum_{j=1}^{J}\sum_{s=1}^{s}\beta_{js} \le 1 .$$

The model includes the following non-negativity conditions.

(4.35) $$A_{ifm}, x_{im}, xs_{im}, xs_{jm}, xt_{ijsm}, xp_{jsm}, q_{jsgm} \ge 0 .$$

Equation (4.36) restricts values of the binary variable to the set of zero and one.

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

Equation (4.37) restricts the number of the harvest units to integer values.

(4.37) *HUM* and *HUB* are non-negative integer variable.

Figure 6 includes a flow chart of procedures that summarizes the models and equations used to complete the study objectives. To determine the number of mowing days per month in each year in a certain region, the soil moisture balance model developed by Allen et al. (1998) is used. This model uses weather data. Likewise, to determine the number of baling days per month in each year in a certain region, both the soil moisture balance model and the drying model of cut grass developed by Rotz and Chen (1985) are used. The number of mowing and baling days per month in each year in a certain region are inserted into an empirical CDF model. The CDF model is used to estimate the number of mowing and baling days per month in a certain region at 95% probability level. Finally, the optimal number of harvest machines and the cost to deliver feedstock to a biorefinery is determined by using the mixed integer mathematical programming model which uses information about the number of mowing and baling days.

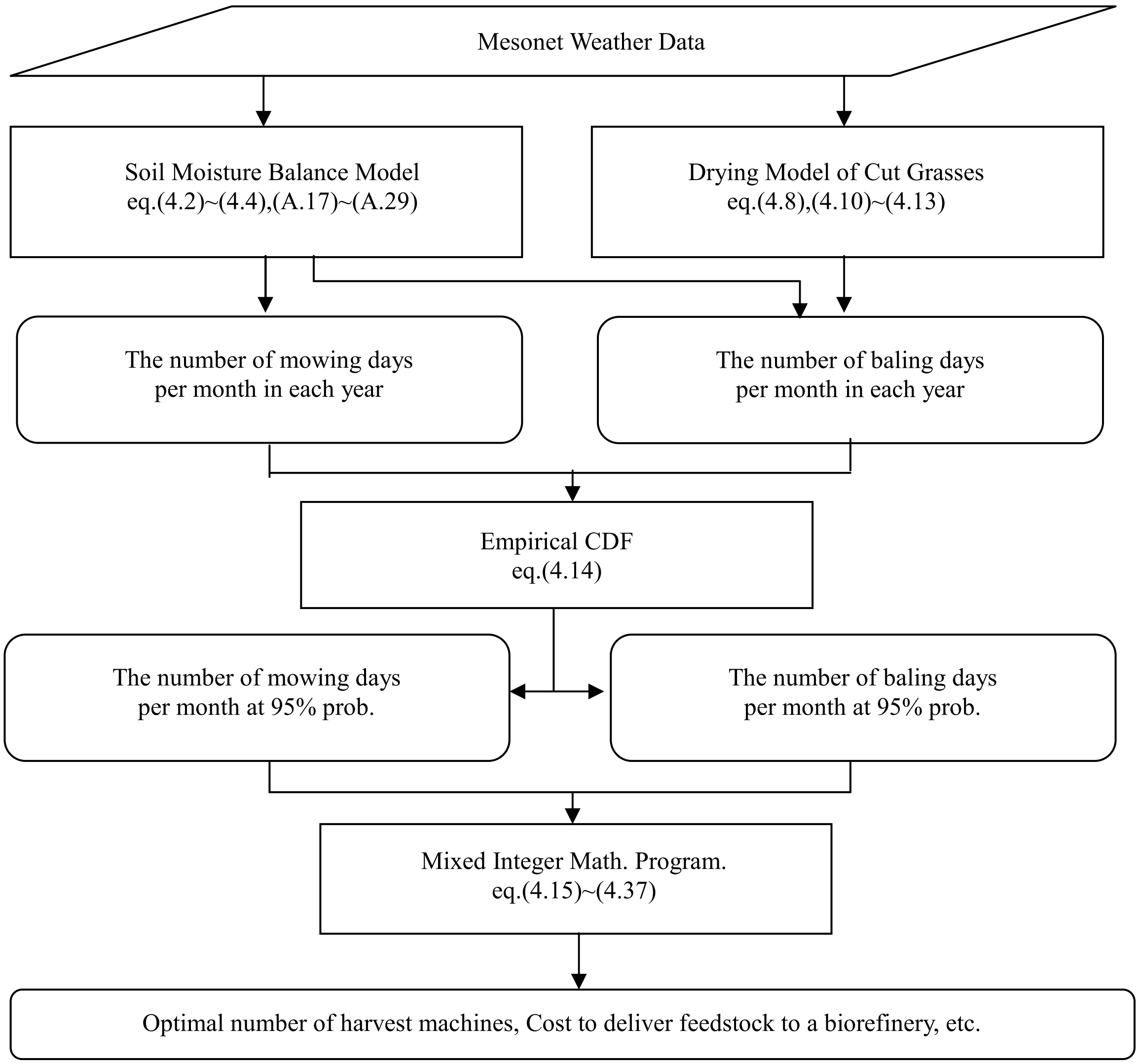

Figure 6. Flow Chart of Procedures of This Study

Data

Data for Soil Moisture Balance Model and Cut Grass Drying Model

Daily meteorological data were used to determine moisture content of the top 15 cm (about six inches) of the soil profile. The following weather variables were used to calculate soil moisture content: daily rainfall (inch), maximum air temperature (°F), daily average air temperature (°F), minimum relative humidity (%), daily average relative humidity (%), daily reference evapotranspiration (mm), daily average wind speed at a height of two meters above ground (m/s), daily average wind speed at a height of ten meters above ground (m/s), and standard deviation of wind speed at ten meters above ground (m/s).

Data (from January 1, 1994 to May 31, 2006) were obtained from the Oklahoma Mesonet. Mesonet is a compound word of "mesoscale" and "network". In meteorology, "mesoscale" refers to weather events that range in size from about one mile to about 150 miles. Mesoscale weather events are phenomenon that might go undetected without densely spaced weather observations. A "network" is an interconnected system. Thus, the Oklahoma Mesonet is a system designed to measure the environment at the size and duration of mesoscale weather events.

The Oklahoma Mesonet consists of over 110 automated stations covering Oklahoma (Figure 7). There is at least one Mesonet station in each of Oklahoma's 77 counties. At each site, the environment is measured by a set of instruments located on or near a ten-meter-tall tower. The observations are transmitted to a central facility

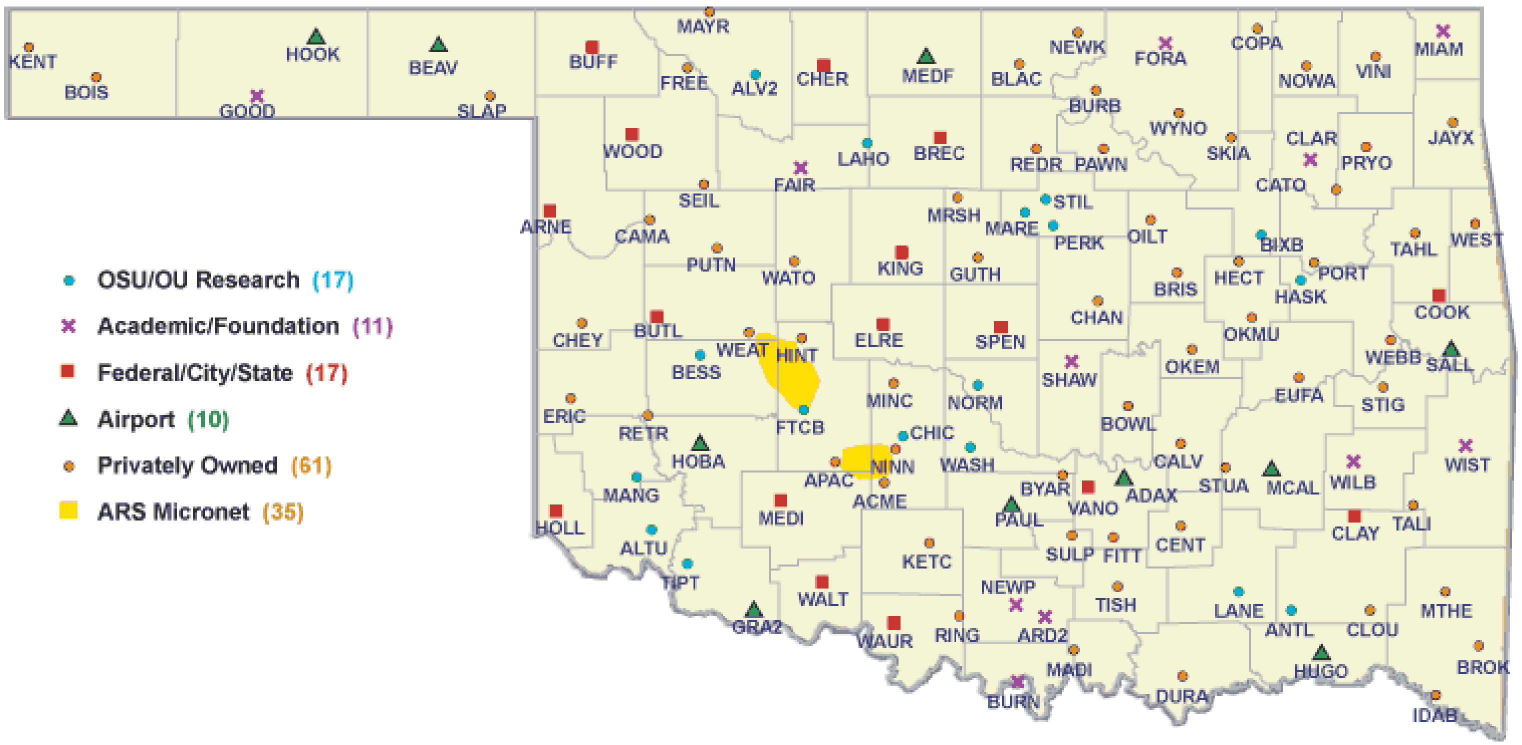

Figure 7. Map of Oklahoma Mesonet Sites

Source: Oklahoma Mesonet

Figure 8. Oklahoma Mesonet Data Collection Station

Source: Oklahoma Mesonet

every five minutes, 24 hours per day year-round (Figure 8).[8] The Oklahoma Mesonet produces daily data which includes a summary of the maximum, minimum, and average level for the observed variables. The averages are determined from the set of five minute observations. These data for each station may be obtained by subscribed members from the Oklahoma Mesonet internet site (http://www.mesonet.org/premium/statistics.html).

One problem encountered in using the daily Oklahoma Mesonet data is that some observations are missing. For a variety of reasons including mechanical problems, lightning strikes, and computer network server downtime, some observations are not recorded and hence, not available. Several methods were used to compensate for missing observations. The first method was to use data provided by another weather service system such as Oklahoma Climate Data (http://climate.ocs.ou.edu), which has daily values for maximum temperature, minimum temperature, precipitation, snowfall, and depth of snow, and the National Climatic Data Center (NCDC, http://hurricane.ncdc.noaa.gov/dly).

The second method was to use data recorded and available from a neighboring Mesonet station. For instance, missing data from the Beaver station located in Beaver County were substituted by data recorded at the Hooker station in adjacent Texas County.

The third method was to estimate values for missing observations. Recorded observations for average wind speed at a height of two meters above ground were frequently missing. In this case, estimates of wind speed at two meters above ground were obtained by regression models. The model is specified as follows

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[8] Weather variables recorded each five minutes are: Barometric Pressure, Rainfall, Relative Humidity at 1.5 m, Solar Radiation, Air Temperature at 9 m, Air Temperature at 1.5 m, Wind Direction at 10 m, Wind Direction Standard Deviation at 10 m, Maximum Wind Speed at 10 m, Maximum Wind Speed at 2 m, Wind Speed at 2 m, Wind Speed at 10 m, Wind Speed Standard Deviation at 10 m, and Vector Wind Speed at 10 m.

(4.38) $$WS2M_t = \beta_1 WSPD_t + \beta_2 WDEV_t + \varepsilon_t$$

where WS2M is an average wind speed at two meters above ground in *t* day, WSPD is an average wind speed at ten meters above ground in *t* day, and WDEV is a standard deviation wind speed at ten meters above ground in *t* day.

Missing average dew point temperatures were estimated from average temperature and average relative humidity. The models are specified as follows

(4.39) $$DAVG_t = \beta_0 + \beta_1 TAVG_t + \beta_2 HAVG_t + \varepsilon_t$$

where DAVG is an average dew point temperature in *t* day, TAVG is an average temperature in *t* day, and HAVG is an average relative humidity in *t* day. The estimation results are presented in Table 7 and 8.

If none of these methods were successful in finding a substitute value for a missing observation, an average value was inserted. For example, if the Beaver station maximum temperature for January 20, 1995 was not available, the average maximum January 20 Beaver station temperature (1994~2006, not including 1995) would be used for the 1995 observation.

The following hourly weather variables were required by the cut grasses drying model: solar insolation (W/m^2), vapor pressure deficit (kPa), relative humidity (fraction), wind speed at a height of two meters above ground (m/second), and rainfall (mm). Unfortunately the Oklahoma Mesonet does not routinely provide hourly data for these variables. Five-minute raw observations were obtained directly from Mesonet personnel (Reader[9]). About 1.37 million five-minute observations were converted into nearly

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[9] Personal communication, August 2006, Climate Information Group, Oklahoma Climatological Survey, Norman, Oklahoma.

Table 7. Results of Estimation of Wind Speed at a Height of Two Meters above Ground

Region (County)	WSPD (Wind Speed at 10m above ground)	WDEV (Standard Deviation of wind speed at 10m above ground)	Number of Observation	R-square
Panhandle (Beaver)	0.73365 (325.86)	-0.08722 (-15.17)	4505	0.9952
West Central (Custer)	0.75619 (246.66)	-0.11753 (-16.00)	2388	0.9957
Southwest (Kiowa)	0.80693 (374.44)	-0.13836 (-21.72)	4522	0.9955
North Central (Alfalfa)	0.79744 (221.84)	-0.10733 (-12.41)	2434	0.9945
Central (Payne)	0.83415 (276.63)	-0.17660 (-26.43)	4520	0.9911
South Central (Johnston)	0.77642 (218.14)	-0.20250 (-23.47)	4440	0.9887
Northeast (Osage)	0.72258 (197.48)	-0.14954 (-15.29)	4498	0.9874
East Central (Muskogee)	0.83145 (258.17)	-0.24022 (-29.79)	4492	0.9921
Southeast (McCurtain)	0.76257 (199.97)	-0.13706 (-16.64)	4530	0.9878

Note: Values in parentheses are t-values.

Table 8. Results of Estimation of Average Dew Point Temperature

Region (County)	Intercept	TAVG (Average Temperature)	HAVG (Average Relative Humidity)	Number of Observation	R-square
Panhandle (Beaver)	-44.773 (-252.37)	0.93960 (546.84)	0.52494 (269.03)	4476	0.9857
West Central (Custer)	-42.891 (-291.61)	0.94801 (691.99)	0.49234 (309.37)	4282	0.9915
Southwest (Kiowa)	-41.491 (-282.53)	0.93862 (687.60)	0.48096 (320.62)	4472	0.9909
North Central (Alfalfa)	-40.959 (-291.48)	0.94310 (823.96)	0.46998 (309.37)	4456	0.9935
Central (Payne)	-40.687 (-348.40)	0.95962 (922.14)	0.45300 (336.94)	4495	0.9952
South Central (Johnston)	-39.493 (-410.91)	0.95688 (1032.02)	0.43862 (394.71)	4507	0.9965
Northeast (Osage)	-40.045 (-406.52)	0.95909 (1015.30)	0.44519 (377.31)	4440	0.9963
East Central (Muskogee)	-38.902 (-440.02)	0.95742 (1235.50)	0.43330 (398.14)	4463	0.9975
Southeast (McCurtain)	-39.022 (-432.49)	0.96026 (1214.20)	0.43033 (400.61)	4401	0.9975

Note: Values in parentheses are t-values.

109,000 hourly observations for each weather station for each weather variable.[10] Methods described previously were used to complete missing observations. Since the biomass material is assumed to be permitted to dry after cutting and prior to raking, the swath density can be assumed to be the same as dry matter yield. An estimated swath density of 1.587 g/m^2 was based upon the assumed switchgrass yield in the region (Taliaferro 2005). Initial moisture content of switchgrass after cutting is also given by Taliaferro. Estimated initial moisture content is 62% for July, 60% for August, 58% for September, 55% for October, and 15% for November through February of following year.

A representative county was selected from each of Oklahoma's nine climate regions. The selected nine counties are shaded in Figure 9. Mesonet data from each of the nine counties were used in combination with the models to determine the number of mowing and baling days for each region. Table 9 includes a list of the weather stations from the nine selected counties used to obtain the required metrological data.

[10] If at least five weather variables are considered from nine weather stations, total five-minute raw observations are about 61.5 million and hourly observations are about 4.9 million.

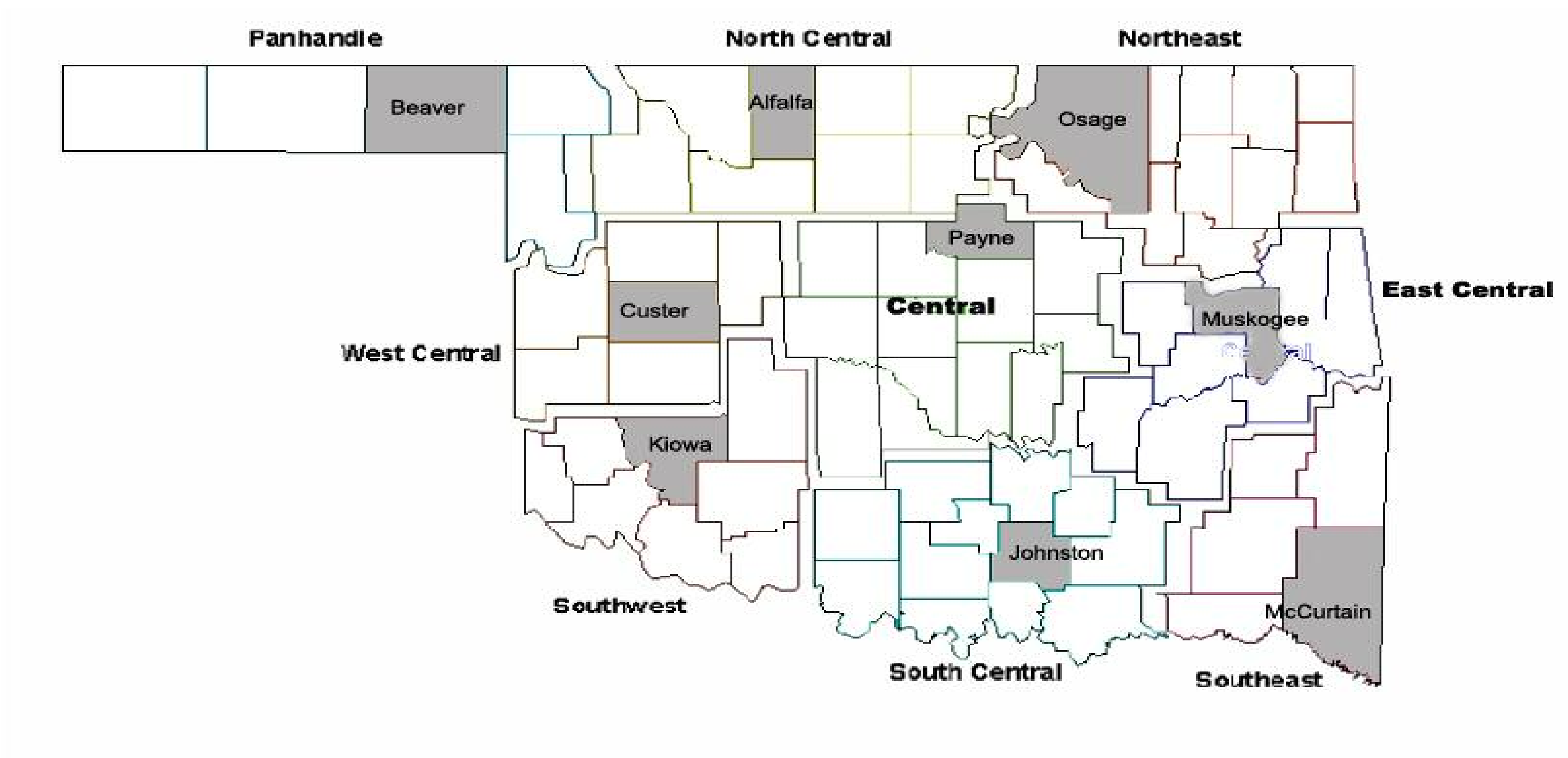

Figure 9. Map of Oklahoma Showing the Climate Divisions: Data from Stations Located in Shaded Counties Were Used

Table 9. Name of Weather Station Selected Each of Nine Counties

Region	County	Weather station
Panhandle	Beaver	Beaver
North Central	Alfalfa	Cherokee
Northeast	Osage	Foraker
West Central	Custer	Butler
Central	Payne	Stillwater
East Central	Muskogee	Haskell
Southwest	Kiowa	Hobart
South Central	Johnston	Tishimingo
Southeast	McCurtain	Idabel

Data and Assumptions for Cost to Deliver Switchgrass to a Biorefinery Using MIP

This study was based on the assumption that a biorefinery would depend exclusively on switchgrass as a single feedstock. In the model, switchgrass production is restricted to cropland. Switchgrass is a perennial that may be planted in March. No harvest is assumed for the establishment year. In subsequent years research has shown that in Oklahoma established switchgrass may be harvested once per year. Harvest may occur as early as July and as late as February of following year (Epplin 1996; Huhnke 2007). Yield estimates for switchgrass were based upon estimates provided by Graham, Allison and Becker (1996) and Fuentes and Taliaferro (2002).

If switchgrass harvest is delayed past September, yield will be reduced by about five percent per month. The model includes a yield adjustment factor to adjust expected yield depending upon month of harvest. This study used the same yield adjustment factors as Mapemba (2005). They were obtained through personal communication from a professional agronomist (Taliaferro 2005). Table 10 shows the switchgrass yield adjustment factors by month.

Table 10. Yield Adjustment Factor for Switchgrass by Month

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
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: Mapemba (2005, p. 98)

Each of Oklahoma's 77 counties is considered to be a potential switchgrass production region. The number of cropland acres available in each county was taken from the 2002 agricultural census. A restriction is included in the model to limit switchgrass production in each county to no more than ten percent of the county's cropland acres.

It is also assumed that the use of this cropland can be acquired at a long term lease rate of $60 per acre per year. The average 2006-2007 cropland cash rental rate for Oklahoma dryland wheat acres was $30 per acre with a range from $10 to $60 per acre (Doye and Sahs 2007). This value is consistent with that reported by the United States Department of Agriculture's Land Values and Cash Rents 2006 Summary. They reported an Oklahoma cropland cash rental rate of $28 per acre. The $60 level was selected to enable management to lease land suitable for seeding to switchgrass production, to compensate for long term rather than an annual cash lease, and to account for an expected supply response that might occur if a private entity were to rent ten percent of the cropland acres in a county.

Establishment and maintenance costs of switchgrass were estimated to be $26 and $3 per acre, respectively. These costs were obtained from budgets prepared by Epplin and Hwang. In addition, it was assumed that in post establishment years, 80 pounds of nitrogen fertilizer would be applied per acre per year to the established switchgrass. The price of nitrogen fertilizer was budgeted at $0.28 per pound (Huhnke 2007).

Eleven counties in the state were selected as viable biorefinery locations: Canadian, Comanche, Custer, Garfield, Jackson, Okmulgee, Payne, Texas, Pontotoc, Washington, and Woodward (Figure 10) (Tembo 2000; Mapemba 2005). These 11 potential biorefinery locations were selected on the basis of biomass relative density, proximity to the potential biomass producing counties, and availability of road

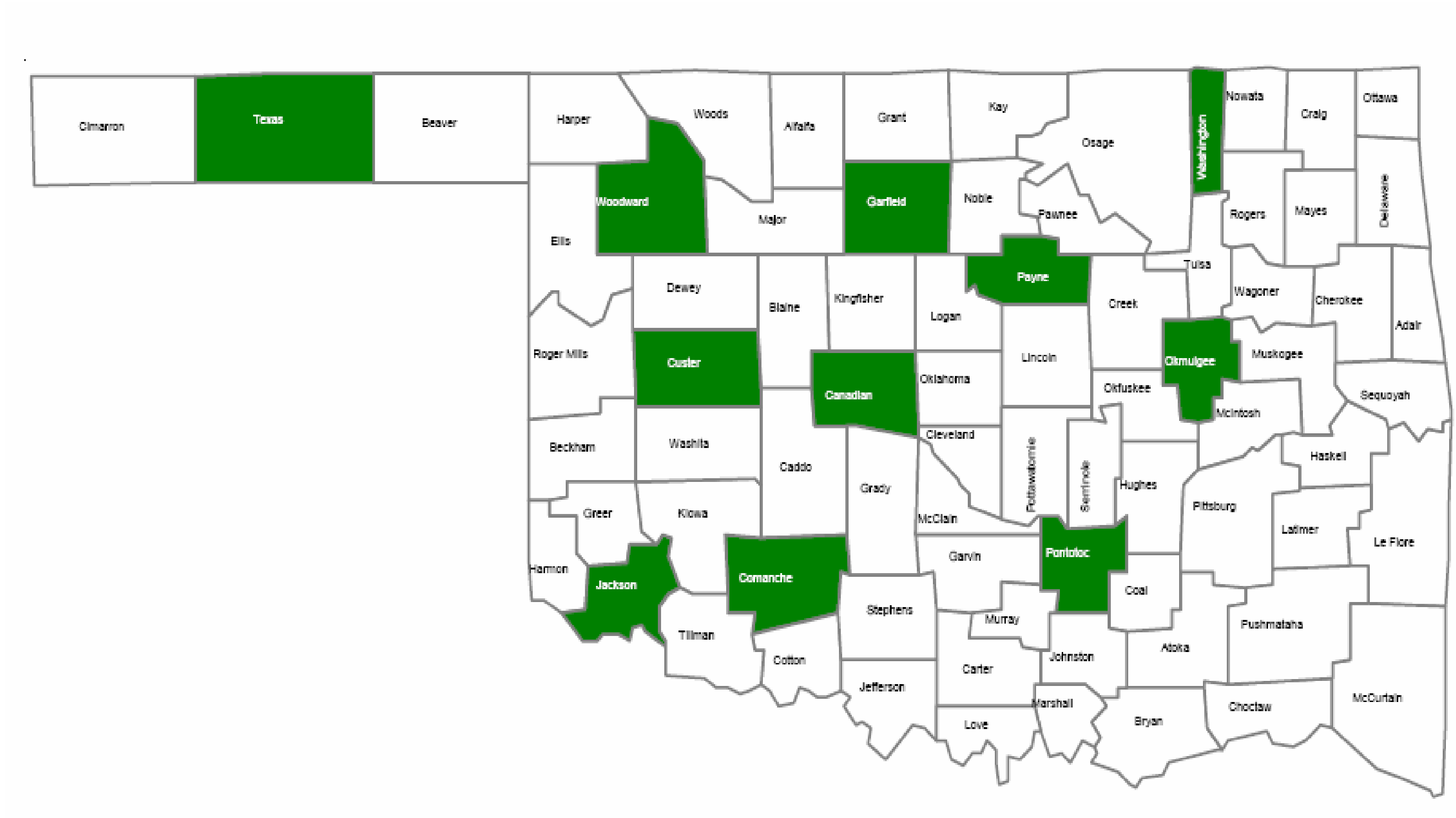

Figure 10. Map Showing Eleven Potential Biorefinery Locations

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 potential biorefinery location was estimated by the distance between the two county's representative points (i.e., the centrally located city) (Mapemba et al. 2007, p.231). Transportation costs were computed using a regression model developed by Bhat, English, and Ojo (1992). The equation of biomass transportation cost is specified as follows

(4. 40) $$TC_{ij} = 34.08 + 1.00 d_{ij}$$

where TC_{ij} is the estimated truckload cost of transporting biomass by truck from production region *i* to biorefinery *j* and d_{ij} is the round-trip distance in miles. Truck capacity was assumed to be 17 dry tons (Bhat, English, and Ojo 1992). The average transportation cost per ton was calculated by dividing TC_{ij} in equation (4.40) by truck capacity of 17 dry tons.

Harvest costs were based upon a major modification of the harvest unit concept as envisioned by Thorsell (2004). Thorsell's harvest unit referred to a coordinated set of harvest machines that consisted of three mowers, three rakes, three balers, nine tractors, a field transporter, and ten laborers to operate these machines. In this study, this harvest unit was separated into two units – mowing and raking-baling-stacking. This separation was conducted because of the differences between the number of workdays for mowing and the number of workdays suitable for baling. Based on expert opinion, raking, baling, and field stacking operations are considered as an integrated activity because these operations are constrained by the number of workdays suitable for baling.

A mowing harvest unit consists of a mower, a tractor, and a laborer. A raking-baling-stacking harvest unit includes three rakes, three balers, six tractors, a field transporter, and seven laborers. Based on the method developed by Thorsell (2004), the annual operating maintenance costs of a mowing harvest unit, and a raking-baling-stacking harvest unit, were estimated. The estimated average annual cost of using a mowing harvest unit and a raking-baling-stacking harvest unit were $58,424 and $470,236, respectively (See Table C-2 and C-3 in Appendix C).

The estimated average capacities are 122 tons per day for a mowing harvest unit and 355 tons per day a raking-baling-stacking harvest unit (See Table C-6 in Appendix C). These capacities are adjusted by month based upon the length of daylight (Table 11). Daily harvest unit capacities were calibrated by month based upon differences from the average length of daylight in March which in Oklahoma has an average day length of 12 hours. Harvest days per month per county were based upon results for the number of mowing days and raking-baling-stacking days estimated by this study. A 95 percent probability level for the number of workdays was used. For example, based upon the empirical probability distribution derived from the Mesonet data, 20 workdays are available at the 95 percent probability level in July. This means that at least 20 July workdays are expected in 19 out of 20 years.

Four different biorefinery sizes were modeled based upon biomass feedstock requirements of either 1,000, or 2,000, or 3,000 or 4,000 dry tons per day. The biorefinery is expected to operate 350 days per year. For each biorefinery size, storage capacity at the biorefinery was assumed equivalent to the tons of biomass that could be

Table 11. Daily Harvest Capacity for a Mowing Harvest Unit and a Raking-Baling-Stacking Harvest Unit of Each Month Adjusted by the Length of Daylight (tons/day)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mowing	102	111	122	134	143	148	146	137	126	114	104	99
Raking-Baling-Stacking	296	322	355	389	417	431	424	399	366	333	303	288

Note: Because the length of daylight is different in each month, daily capacity was adjusted by month. March was assumed to be the base month. Adjustment coefficients were computed by the proportion of length of daylight in each month based on length of daylight of March (12 hours). Adjustment coefficients are 0.83 for January, 0.91 for February, 1.00 for March, 1.10 for April, 1.18 for May, 1.21 for June, 1.19 for July, 1.12 for August, 1.03 for September, 0.94 for October, 0.85 for November, and 0.81 for December. Thus, daily capacity of a mowing harvest unit in August was computed as: 122 tons per day * 1.12 = 137 tons per day.

processed in three weeks (i.e., 21,000, 42,000, 63,000, and 84,000 tons). Minimum inventory at the biorefinery facility was assumed to be equal to zero. Storage losses at the biorefinery were assumed to be equal to one percent per month. Precise estimates of storage losses are not available (Huhnke, 2007).

Field storage capacity is not limited. The cost of field storage that includes the cost of covering stored material with a plastic trap was estimated at $2 per ton of biomass regardless of storage length. Field storage losses are also assumed to be one percent per month (Mapemba et al. 2007, p. 232).

CHAPTER V

RESULTS

The Number of Workdays for Harvesting Switchgrass

Empirical CDFs were computed for each month for each of nine selected counties for both mowing days and baling days. It was assumed that the number of available mowing and baling days for each year are independent across years. This means that the number of available workdays for one year is not affected by the number of workdays in prior years. This assumption can be used because weather variables such as rainfall and evapotranspiration are independent from year to year.

Table 12 and 13 provide the number of available mowing and baling days, respectively, per month during which switchgrass harvesting can occur at no less than 50%, 70%, 80%, 90%, and 95% probability levels. However, harvest of switchgrass is liminted to July through February of the following year. Figure 11 through 22 show the 95% probability level for the number of days available for mowing and baling by month for each of the nine regions. For a given location, month, and year, the number of baling days does not exceed the number of mowing days. In addition to tractability, baling requires that the moisture content of the cut switchgrass not exceed 15%. However, in some months, (i.e. November, December, January, February, and March) the standing crop is relatively dry, and if the moisture content is less than 15% baling can proceed immediately after cutting. A 90%

probability represents the minimum number of suitable days that can be anticipated in nine out of ten years. The 50% probability number is the mean or average number of workdays over the years for which data were available. For instance, for the month of August, there are 24 mowing days and 21.5 baling days at the 50% probability level in the Southwest region of Oklahoma. Hence, the number of days for mowing and baling averaged 24 and 21.5, respectively, in the Southwest area of Oklahoma for the month of August from 1994 to 2005, the years for which Mesonet data are available. However, there are only 15 mowing days and nine baling days at the 95% probability level (19 out of 20 years) in the Southwest region. In other words, at least 15 field workdays for mowing switchgrass are expected in the Southwest region at the 95% probability level in August. Likewise, at least nine days for baling are expected in the Southwest region at the 95% probability level in August.

As expected, the number of available mowing and baling days per month are less in the southeast region of Oklahoma, which receives more precipitation, and more in the Panhandle region, that receives less precipitation.

In the Panhandle, baling could be conducted in 19 of 20 years on at least 197 days (54% of the days). However, in the Southeast region, baling could be conducted on only 174 days in 19 of 20 years (48% of the days). When averaged across regions, at the 95% level, November has an average of 13.8 baling days (46%) and July has an average of 20.3 baling days (66%). This information may be used to determine the investment required in harvest machines to provide LCB to a biorefinery.

Table 12. The Number of Mowing Days for Switchgrass for Five Probability Levels from an Empirical CDF for Oklahoma, Based upon Oklahoma Mesonet Data from 1994-2006

Region (County)	Prob. Level (%)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Panhandle (Beaver)	95	21.0	15.0	17.0	16.0	15.0	15.0	17.0	15.0	19.0	16.0	10.0	21.0
	90	21.0	19.0	19.0	19.0	19.0	16.0	18.0	20.0	21.0	20.0	23.0	23.0
	80	24.0	19.0	20.0	19.0	21.0	18.0	19.0	21.0	21.0	23.0	24.0	23.0
	70	24.0	21.0	21.0	21.0	23.0	18.0	21.0	23.0	22.0	23.0	25.0	26.0
	50	27.0	24.0	24.5	22.5	23.5	20.0	23.0	24.0	23.0	25.0	27.5	27.5
West Central (Custer)	95	18.0	17.0	18.0	17.0	15.0	14.0	19.0	15.0	16.0	17.0	12.0	19.0
	90	19.0	17.0	19.0	19.0	15.0	15.0	21.0	19.0	18.0	18.0	20.0	20.0
	80	20.0	19.0	19.0	20.0	16.0	16.0	23.0	19.0	18.0	18.0	21.0	22.0
	70	22.0	19.0	19.0	21.0	18.0	16.0	23.0	21.0	22.0	21.0	22.0	23.0
	50	25.5	22.5	24.5	22.0	21.0	20.0	24.0	24.0	22.0	24.5	24.0	25.0
Southwest (Kiowa)	95	16.0	16.0	19.0	15.0	15.0	11.0	20.0	15.0	15.0	15.0	14.0	19.0
	90	19.0	17.0	20.0	19.0	16.0	18.0	21.0	19.0	19.0	18.0	18.0	19.0
	80	19.0	17.0	21.0	19.0	17.0	18.0	22.0	22.0	22.0	18.0	19.0	22.0
	70	21.0	18.0	22.0	21.0	19.0	18.0	22.0	22.0	23.0	21.0	20.0	24.0
	50	25.5	21.0	22.5	22.0	21.0	20.5	23.0	24.0	25.0	22.5	23.0	25.0
North Central (Alfalfa)	95	18.0	18.0	16.0	15.0	17.0	16.0	17.0	18.0	20.0	17.0	14.0	15.0
	90	21.0	19.0	18.0	17.0	19.0	17.0	20.0	18.0	20.0	17.0	18.0	20.0
	80	22.0	19.0	19.0	18.0	20.0	17.0	21.0	19.0	22.0	19.0	20.0	21.0
	70	23.0	19.0	21.0	18.0	20.0	17.0	21.0	20.0	22.0	21.0	23.0	23.0
	50	25.0	21.5	23.0	22.0	21.0	19.5	23.5	23.5	23.0	22.5	26.5	24.0
Central (Payne)	95	19.0	18.0	16.0	17.0	16.0	14.0	19.0	17.0	18.0	16.0	11.0	18.0
	90	20.0	20.0	19.0	17.0	16.0	15.0	22.0	19.0	19.0	17.0	17.0	19.0
	80	21.0	21.0	19.0	19.0	17.0	15.0	22.0	20.0	21.0	18.0	20.0	21.0
	70	22.0	21.0	19.0	20.0	17.0	18.0	23.0	23.0	21.0	18.0	21.0	21.0
	50	25.5	22.5	23.5	21.0	22.5	21.5	24.5	25.0	21.5	21.5	23.0	24.0
South Central (Johnston)	95	13.0	9.0	18.0	14.0	14.0	15.0	17.0	19.0	16.0	13.0	13.0	16.0
	90	18.0	14.0	19.0	17.0	16.0	16.0	18.0	19.0	17.0	14.0	13.0	17.0
	80	18.0	15.0	19.0	19.0	18.0	17.0	20.0	23.0	18.0	17.0	14.0	18.0
	70	20.0	16.0	19.0	19.0	19.0	18.0	20.0	24.0	19.0	18.0	15.0	19.0
	50	22.0	19.5	22.5	22.0	21.5	23.0	24.0	25.0	22.0	22.5	22.0	23.0
Northeast (Osage)	95	16.0	16.0	12.0	16.0	16.0	11.0	16.0	20.0	17.0	16.0	14.0	18.0
	90	19.0	17.0	20.0	18.0	17.0	14.0	19.0	21.0	19.0	17.0	17.0	19.0
	80	20.0	17.0	21.0	18.0	18.0	14.0	19.0	21.0	19.0	19.0	19.0	19.0
	70	22.0	20.0	21.0	19.0	18.0	18.0	21.0	22.0	20.0	20.0	20.0	20.0
	50	24.0	21.0	21.5	20.0	20.5	18.5	24.0	24.5	23.0	21.5	24.5	23.5
East Central (Muskogee)	95	17.0	10.0	18.0	16.0	15.0	16.0	20.0	19.0	17.0	17.0	9.0	15.0
	90	17.0	15.0	19.0	18.0	16.0	16.0	21.0	20.0	19.0	17.0	15.0	18.0
	80	19.0	17.0	20.0	18.0	17.0	17.0	22.0	21.0	20.0	19.0	16.0	19.0
	70	19.0	17.0	20.0	18.0	17.0	19.0	22.0	21.0	20.0	20.0	16.0	21.0
	50	23.5	21.0	22.0	20.5	20.5	20.0	24.0	25.5	21.5	22.0	20.5	23.0
Southeast (McCurtain)	95	15.0	12.0	15.0	11.0	16.0	12.0	18.0	18.0	18.0	14.0	13.0	12.0
	90	15.0	14.0	16.0	18.0	17.0	18.0	20.0	21.0	18.0	16.0	14.0	18.0
	80	16.0	15.0	17.0	19.0	19.0	18.0	20.0	21.0	20.0	17.0	14.0	18.0
	70	19.0	16.0	17.0	19.0	19.0	20.0	23.0	24.0	21.0	19.0	15.0	19.0
	50	21.5	17.5	19.0	21.5	21.5	21.0	24.0	25.5	23.5	22.5	21.0	21.5

Table 13. The Number of Baling Days for Switchgrass for Five Probability Levels from an Empirical CDF for Oklahoma, Based upon Oklahoma Mesonet Data from 1994-2006

Region (County)	Prob. Level (%)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Panhandle (Beaver)	95	20.0	14.0	17.0	9.0	8.0	11.0	15.0	14.0	11.0	11.0	9.0	21.0
	90	21.0	19.0	18.0	12.0	13.0	12.0	16.0	17.0	15.0	11.0	23.0	23.0
	80	24.0	19.0	19.0	12.0	16.0	12.0	17.0	19.0	15.0	12.0	24.0	23.0
	70	24.0	21.0	20.0	14.0	17.0	13.0	17.0	19.0	16.0	15.0	24.0	26.0
	50	27.0	24.0	24.0	15.5	19.0	17.5	20.5	20.5	19.0	17.5	27.5	27.5
West Central (Custer)	95	18.0	17.0	18.0	11.0	10.0	8.0	16.0	12.0	8.0	3.0	12.0	18.0
	90	19.0	17.0	18.0	12.0	11.0	11.0	18.0	14.0	11.0	9.0	19.0	19.0
	80	20.0	17.0	18.0	12.0	12.0	11.0	18.0	16.0	13.0	12.0	21.0	21.0
	70	21.0	19.0	19.0	12.0	12.0	11.0	21.0	20.0	15.0	14.0	22.0	23.0
	50	25.0	22.5	22.5	15.0	15.0	16.5	21.5	22.0	17.5	16.0	23.5	25.0
Southwest (Kiowa)	95	16.0	15.0	19.0	10.0	9.0	8.0	15.0	9.0	8.0	5.0	12.0	19.0
	90	19.0	17.0	20.0	11.0	10.0	8.0	19.0	16.0	16.0	6.0	18.0	19.0
	80	19.0	17.0	20.0	12.0	12.0	12.0	19.0	18.0	16.0	10.0	18.0	22.0
	70	21.0	18.0	21.0	14.0	14.0	13.0	20.0	18.0	17.0	11.0	20.0	23.0
	50	25.5	21.0	22.0	15.5	16.0	18.0	21.5	21.5	20.0	14.5	22.0	25.0
North Central (Alfalfa)	95	16.0	17.0	14.0	11.0	11.0	13.0	16.0	14.0	13.0	7.0	11.0	13.0
	90	21.0	18.0	17.0	11.0	14.0	14.0	17.0	17.0	14.0	8.0	18.0	20.0
	80	22.0	18.0	19.0	11.0	15.0	14.0	19.0	17.0	15.0	9.0	18.0	20.0
	70	23.0	19.0	21.0	11.0	16.0	15.0	19.0	18.0	15.0	10.0	22.0	21.0
	50	25.0	21.5	23.0	14.5	18.0	17.0	20.5	22.0	18.0	15.0	26.0	24.0
Central (Payne)	95	18.0	17.0	16.0	10.0	10.0	10.0	16.0	14.0	12.0	5.0	11.0	17.0
	90	18.0	20.0	18.0	11.0	11.0	11.0	17.0	15.0	13.0	5.0	15.0	18.0
	80	20.0	20.0	19.0	12.0	11.0	12.0	19.0	16.0	13.0	9.0	18.0	19.0
	70	21.0	20.0	19.0	12.0	13.0	14.0	20.0	20.0	15.0	11.0	20.0	21.0
	50	25.5	21.5	22.5	14.5	16.0	18.5	22.5	22.5	16.0	12.0	22.5	23.5
South Central (Johnston)	95	12.0	9.0	17.0	8.0	9.0	11.0	15.0	14.0	12.0	5.0	12.0	16.0
	90	17.0	14.0	19.0	9.0	12.0	11.0	15.0	14.0	13.0	7.0	13.0	17.0
	80	18.0	15.0	19.0	9.0	13.0	14.0	16.0	20.0	14.0	8.0	13.0	18.0
	70	20.0	16.0	19.0	13.0	13.0	16.0	17.0	20.0	14.0	10.0	14.0	18.0
	50	21.5	19.5	22.5	15.0	16.5	19.0	22.0	23.0	17.0	14.5	21.0	23.0
Northeast (Osage)	95	15.0	15.0	12.0	8.0	10.0	8.0	13.0	12.0	9.0	6.0	12.0	15.0
	90	19.0	16.0	19.0	10.0	11.0	9.0	13.0	15.0	11.0	10.0	16.0	17.0
	80	19.0	17.0	20.0	11.0	13.0	9.0	17.0	16.0	12.0	10.0	18.0	19.0
	70	20.0	18.0	20.0	12.0	14.0	13.0	17.0	19.0	14.0	11.0	19.0	19.0
	50	23.5	20.5	21.0	12.0	15.0	14.5	18.5	20.5	17.5	13.0	24.5	23.0
East Central (Muskogee)	95	15.0	8.0	17.0	9.0	9.0	10.0	16.0	15.0	9.0	6.0	8.0	15.0
	90	16.0	15.0	18.0	10.0	11.0	12.0	17.0	17.0	10.0	7.0	13.0	16.0
	80	18.0	15.0	18.0	12.0	12.0	12.0	17.0	18.0	12.0	10.0	13.0	17.0
	70	18.0	16.0	19.0	13.0	13.0	14.0	18.0	20.0	14.0	12.0	14.0	19.0
	50	23.5	20.0	21.5	13.5	16.5	15.5	21.0	21.0	17.5	13.5	19.0	22.5
Southeast (McCurtain)	95	11.0	10.0	15.0	5.0	8.0	4.0	16.0	13.0	11.0	2.0	10.0	10.0
	90	12.0	13.0	15.0	8.0	11.0	11.0	16.0	15.0	13.0	7.0	11.0	15.0
	80	14.0	14.0	17.0	11.0	12.0	12.0	18.0	18.0	14.0	9.0	12.0	15.0
	70	16.0	14.0	17.0	12.0	14.0	15.0	19.0	21.0	17.0	9.0	14.0	17.0
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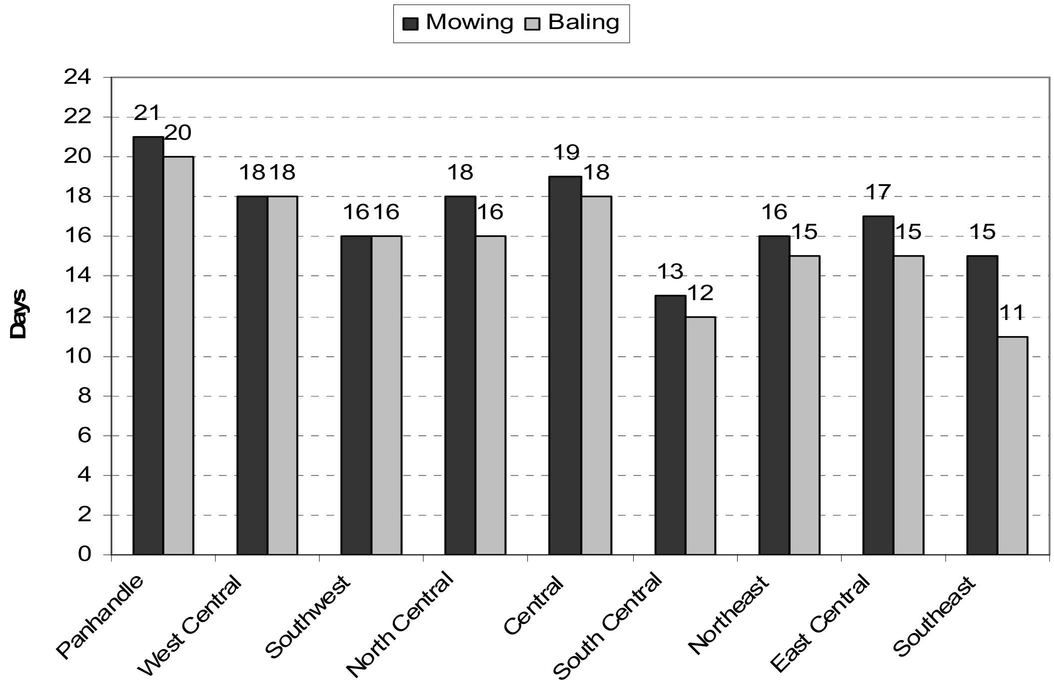

Figure 11. The Number of Mowing & Baling Days for January at 95% Probability Level

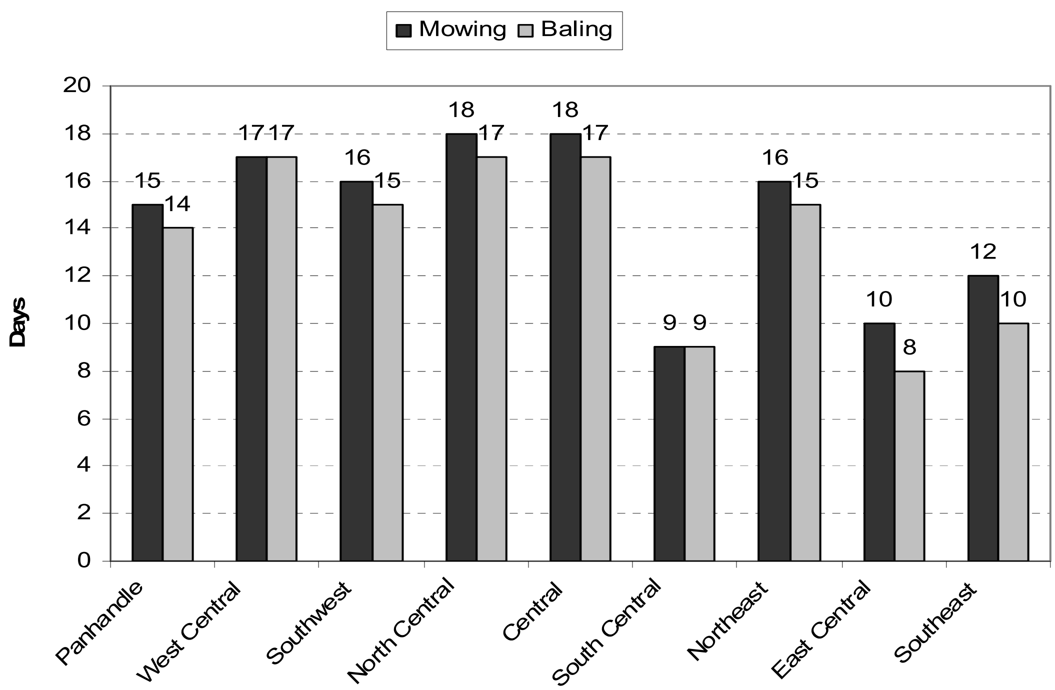

Figure 12. The Number of Mowing & Baling Days for February at 95% Probability Level

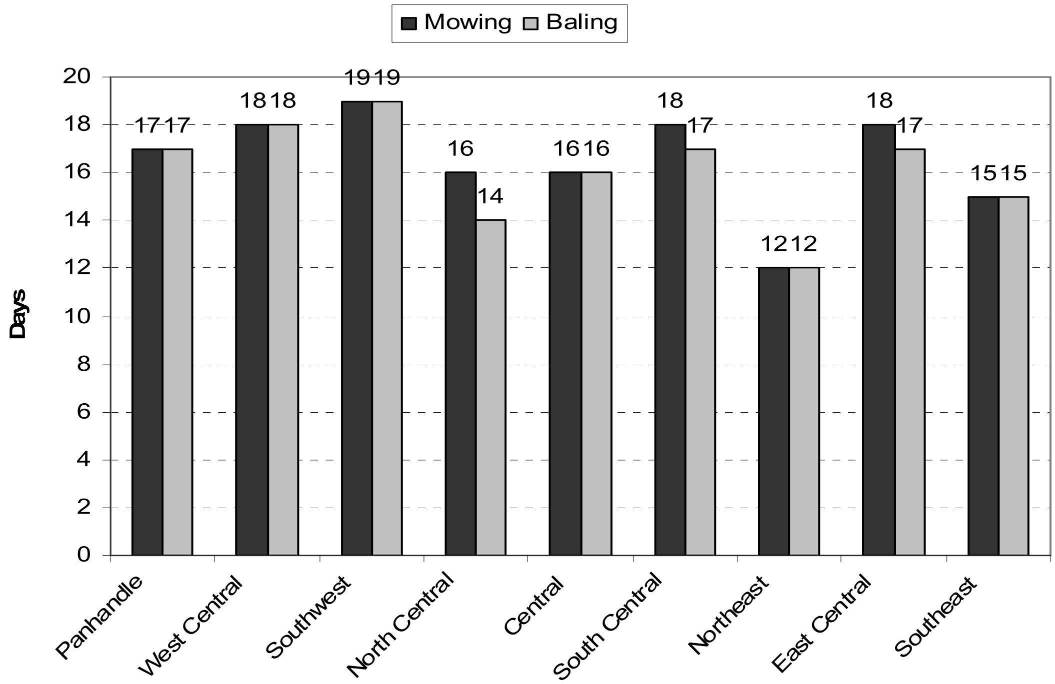

Figure 13. The Number of Mowing & Baling Days for March at 95% Probability Level

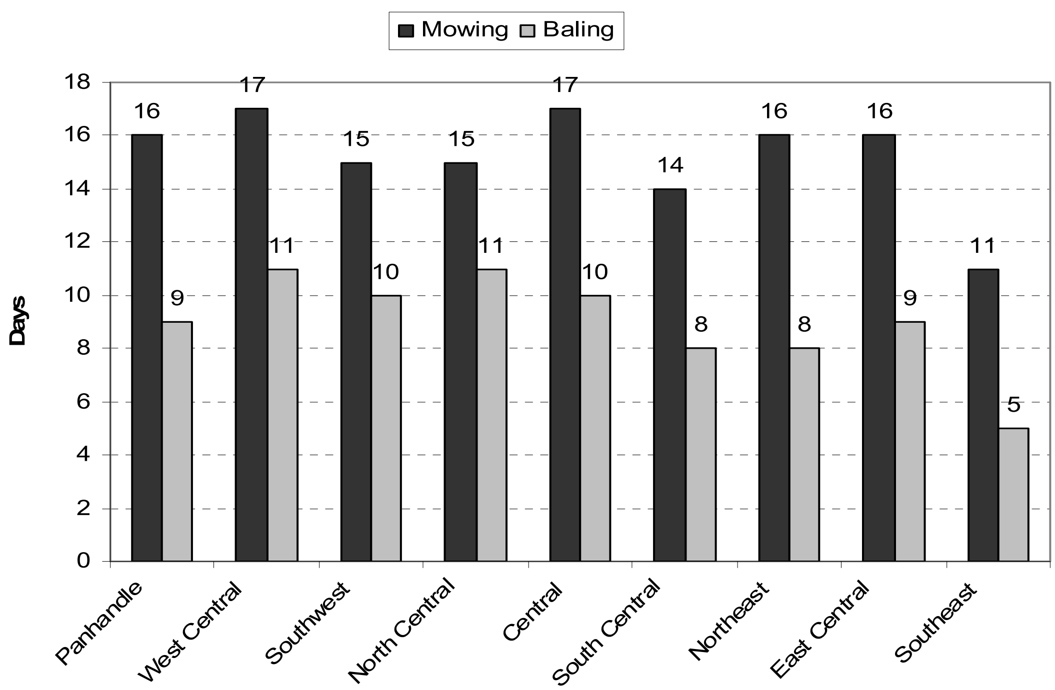

Figure 14. The Number of Mowing & Baling Days for April at 95% Probability Level

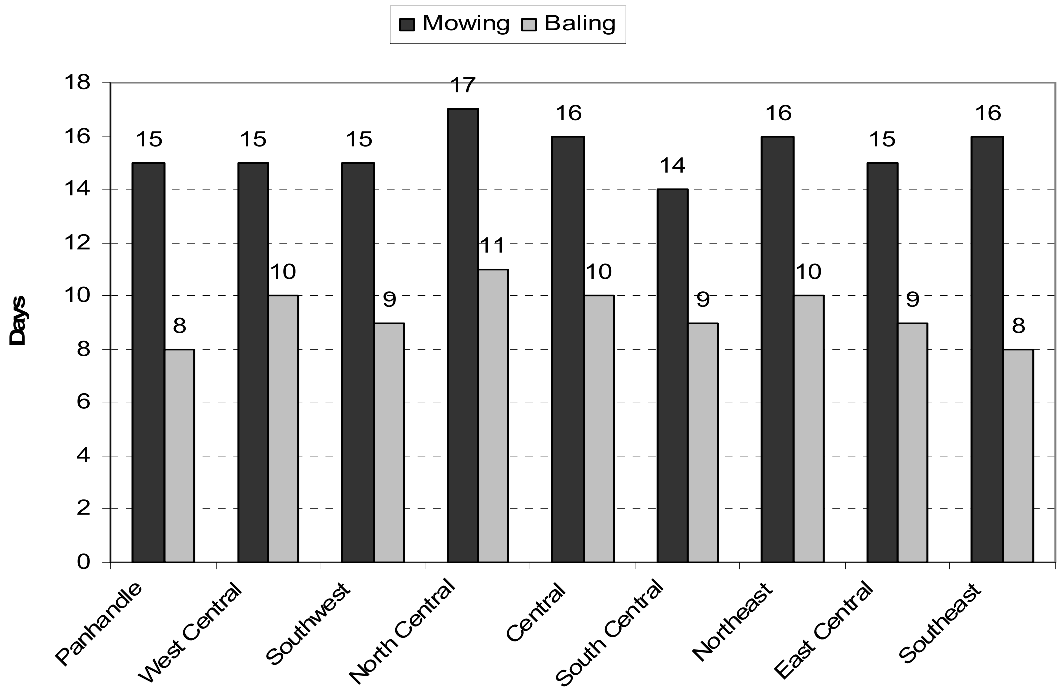

Figure 15. **The Number of Mowing & Baling Days for May at 95% Probability Level**

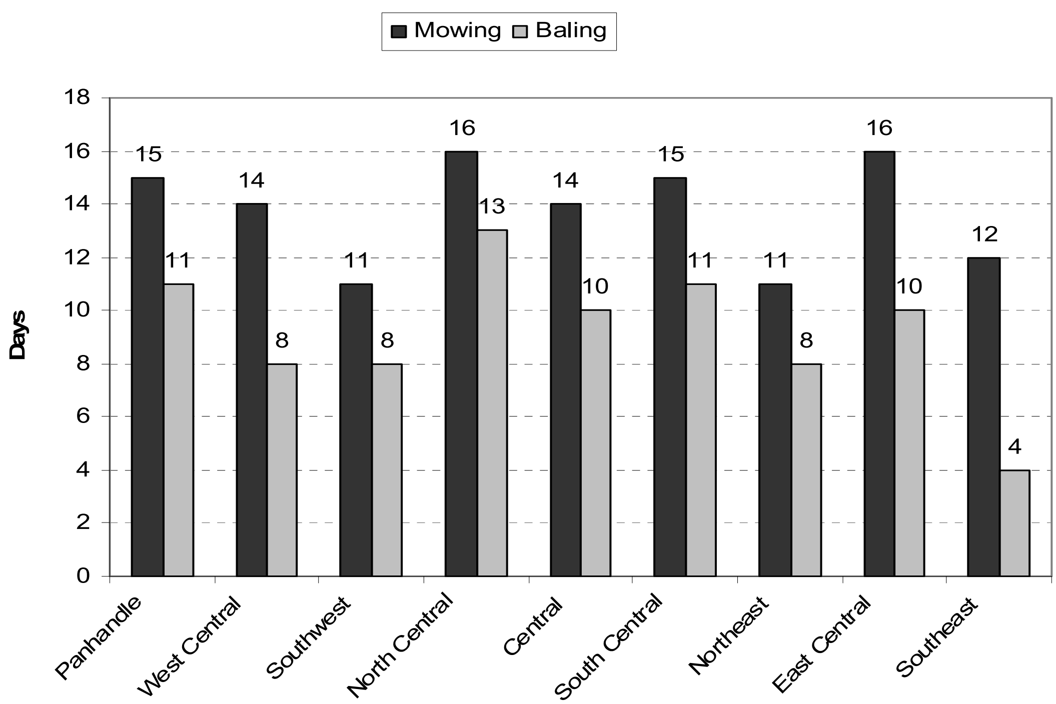

Figure 16. **The Number of Mowing & Baling Days for June at 95% Probability Level**

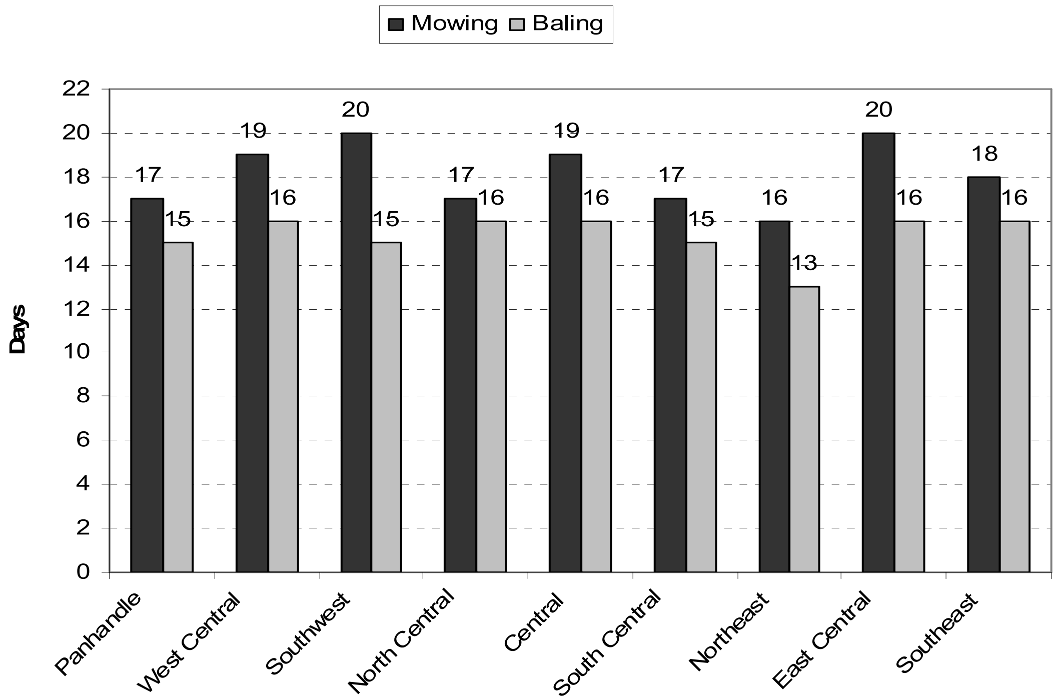

Figure 17. The Number of Mowing & Baling Days for July at 95% Probability Level

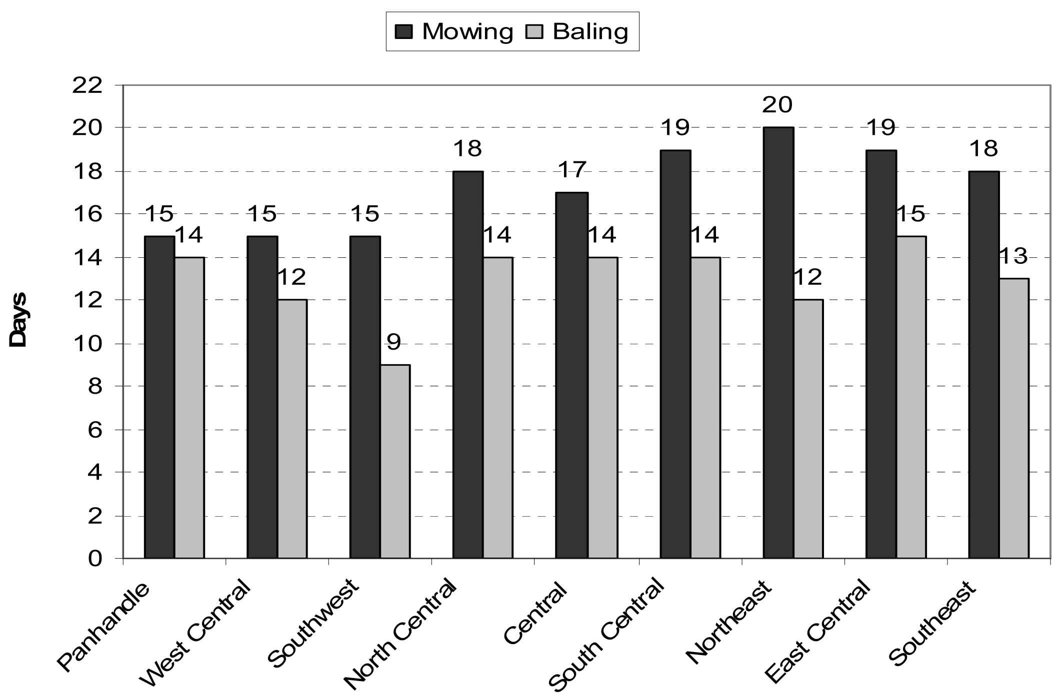

Figure 18. The Number of Mowing & Baling Days for August at 95% Probability Level

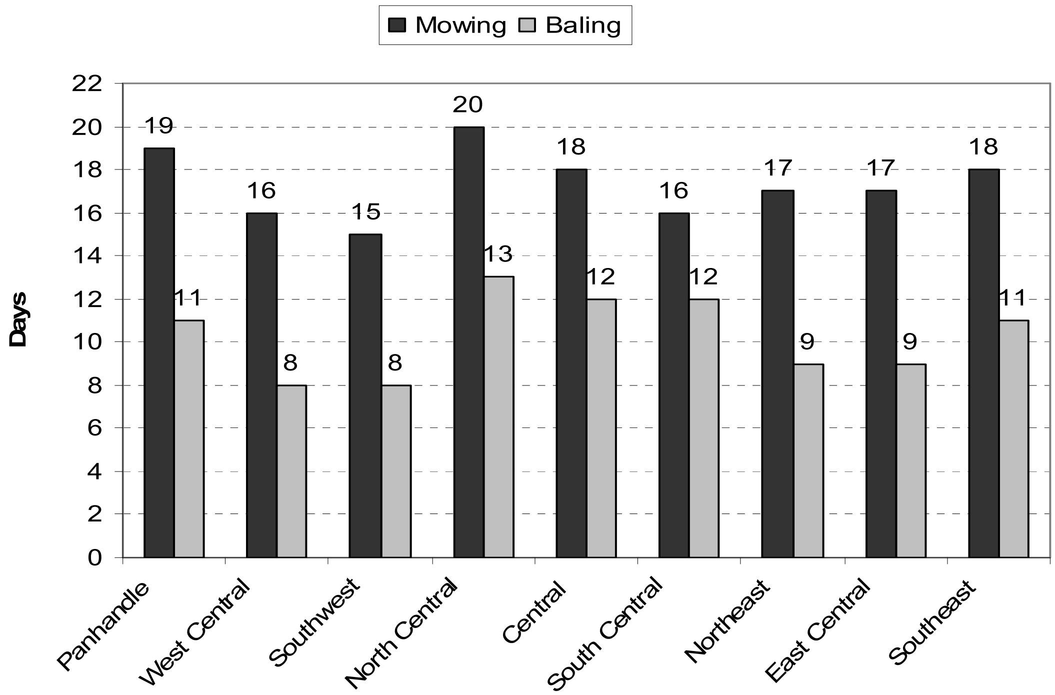

Figure 19. The Number of Mowing & Baling Days for September at 95% Probability Level

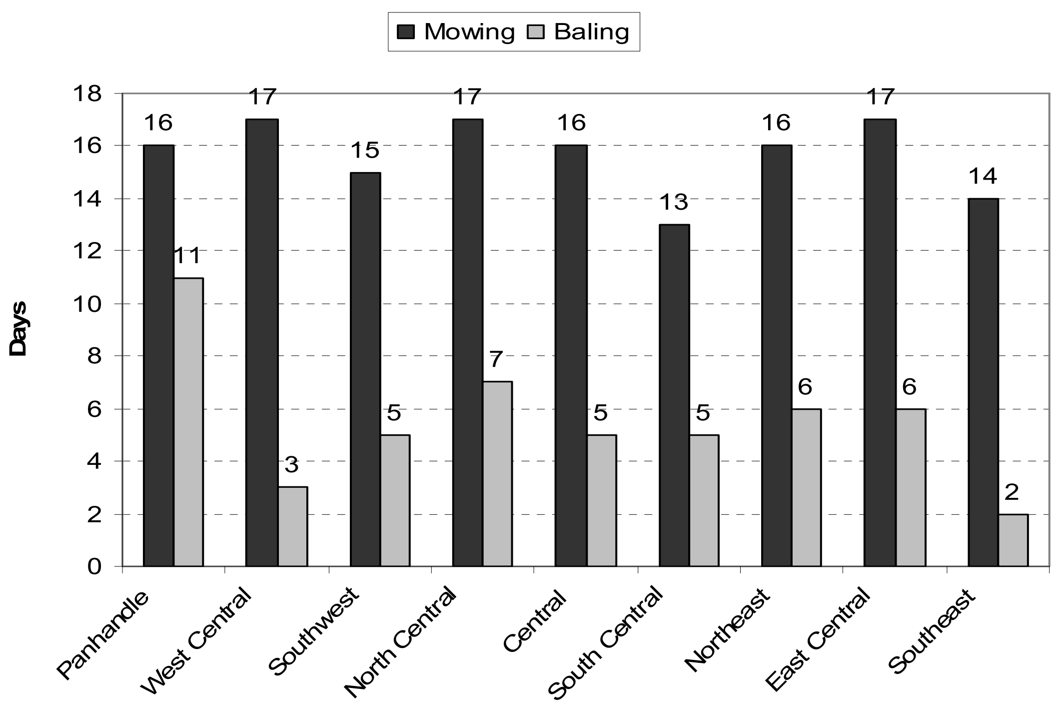

Figure 20. The Number of Mowing & Baling Days for October at 95% Probability Level

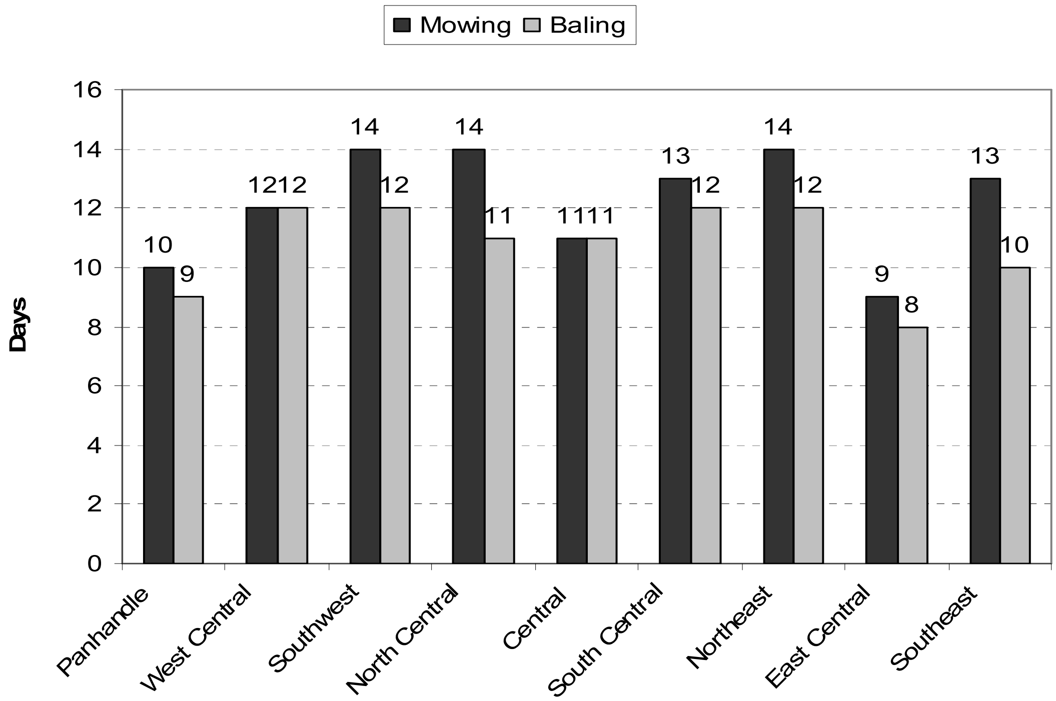

Figure 21. The Number of Mowing & Baling Days for November at 95% Probability Level

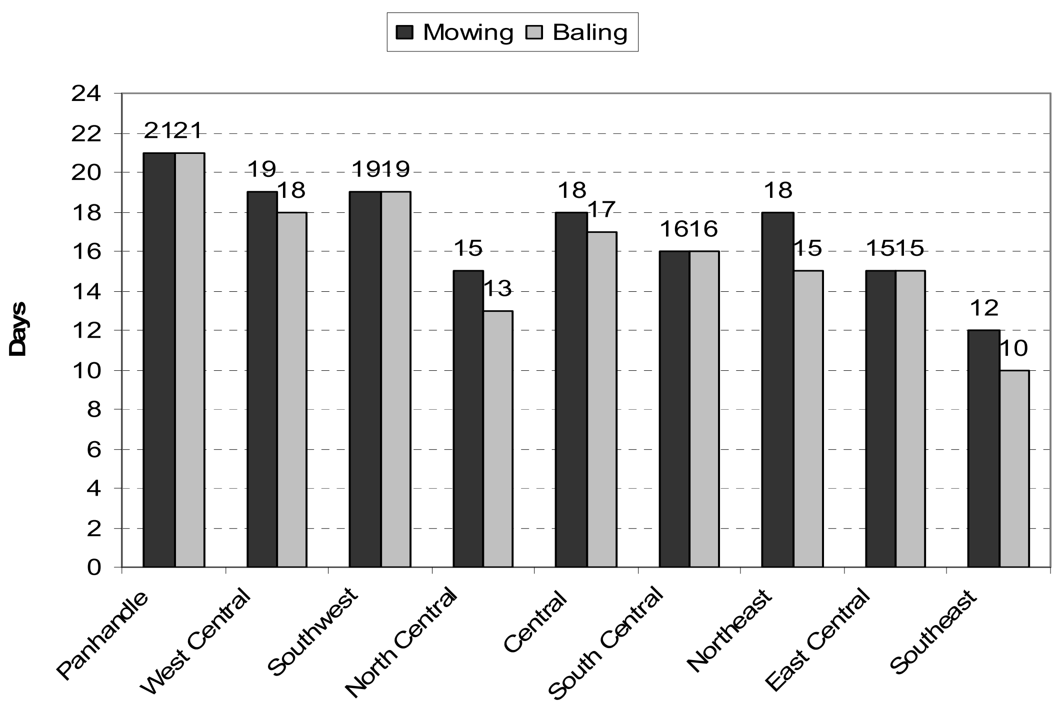

Figure 22. The Number of Mowing & Baling Days for December at 95% Probability Level

Results of Solved Models with Four Different Workday Levels

Table 14 includes a summary of results from the four different assumptions for the number of workdays available in each month per county in which switchgrass could be harvested: Base workdays (WD), Reinschmiedt workdays, Most workdays, and Least workdays.

In the base WD model, the number of mowing days and raking-baling-stacking days estimated at the 95% probability level were used as the number of workdays. The number of workdays obtained from Reinschmiedt's study was used in the Reinschmiedt WD model. Since this study did not separate mowing days and raking-baling-stacking days, the number of workdays for mowing and raking-baling-stacking was considered to be identical. Mapemba (2005) used Reinschmiedt's estimates. For the Most WD model the number of workdays available in each month, regardless of type of harvesting operation, for all counties was assumed to be 30 days. For contrast, the number of workdays was assumed to be three days available in each month in the Least WD model.[11] Both Most WD and Least WD models were based upon extreme assumptions.

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[11] Total cost of using one mowing harvest unit and raking-baling-stacking harvest unit is estimated to be $58,424 and $470,236 per year, respectively, for the Base WD, the Reinschmiedt WD, and the Most WD model. However; in the Least WD model, the number of workdays was fixed at three days per month. Since switchgrass harvest is limited to eight months, available harvest days were restricted to 24 per year. Actually, 24 days was almost the same as the workdays for a month. Thus, switchgrass seemed to be harvested in one month in the Least WD model. Consequently, the fixed cost for machines should be increased and the labor cost should be reduced. Thus, average annual cost of using a harvest unit for the Least WD model should be reestimated. The estimated average annual cost of using a mowing harvest unit and a raking-baling-stacking harvest unit were $69,824 and $681,348, respectively (see Table C-4 and C-5 in Appendix C).

Table 14. Comparison of Results for Estimated Costs, Number of Harvest Units, Average Investment in Harvest Machines and Acres and Tons Harvested, to Provide a Flow of Switchgrass Feedstock to a 2,000 Dry Tons per Day Biorefinery for the Base Model from Reinschmiedt's Workdays, Most Workdays, and Least Workdays

	Model Comparison			
	Base WD[a]	Reinschmiedt WD[b]	Most WD[c]	Least WD[d]
Costs				
Land rent cost ($/ton)	10.77	12.32	10.68	10.73
Field cost ($/ton)[e]	9.23	10.55	9.15	9.19
Harvest cost ($/ton)	17.04	12.61	8.02	108.54
Field Storage cost ($/ton)	0.58	0.57	0.58	0.58
Transportation cost ($/ton)	12.07	10.32	11.95	11.96
Total cost of delivered feedstock ($/ton)	49.68	46.38	40.38	141.00
Other results				
Harvest units for mowing (number)[f]	48	41	26	255
Harvest units for raking-baling-staking (number)[g]	20	14	9	88
Average investment in harvest machines ($,000)	11,281	8,214	5,265	42,091
Average distance hauled (miles)	91	80	90	88
Harvested acres	128,633	146,156	127,647	128,070
Total biomass harvested (tons)	716,681	711,884	716,993	716,473
Plant location	Okmulgee	Canadian	Okmulgee	Okmulgee

[a] The number of workdays for harvesting switchgrass is given by results from this study.
[b] The number of workdays for harvesting switchgrass is given by results from the study of Reinschmiedt (1973).
[c] The number of workdays for harvesting switchgrass is assumed to be 30 days per month.
[d] The number of workdays for harvesting switchgrass is assumed to be three days per month.
[e] Field cost includes amortized establishment, maintenance, and fertilizer costs.
[f] A harvest unit for mowing includes one mower, one tractor, and one worker.
[g] A harvest unit for raking-baling-stacking includes three rakes, three balers, one transport stacker, six tractors, and seven workers.

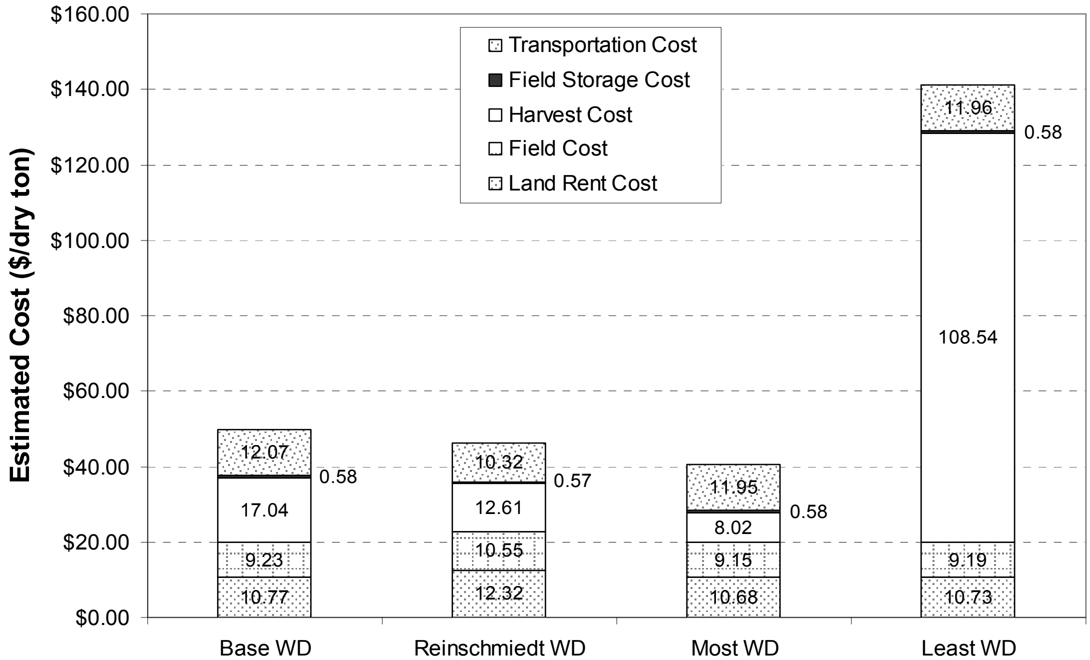

Figure 23. Estimated Cost to Deliver a Flow of Switchgrass Feedstock to a 2,000 Dry Tons per Day Biorefinery for the Base WD, Reinschmiedt WD, Most WD, and Least WD Models

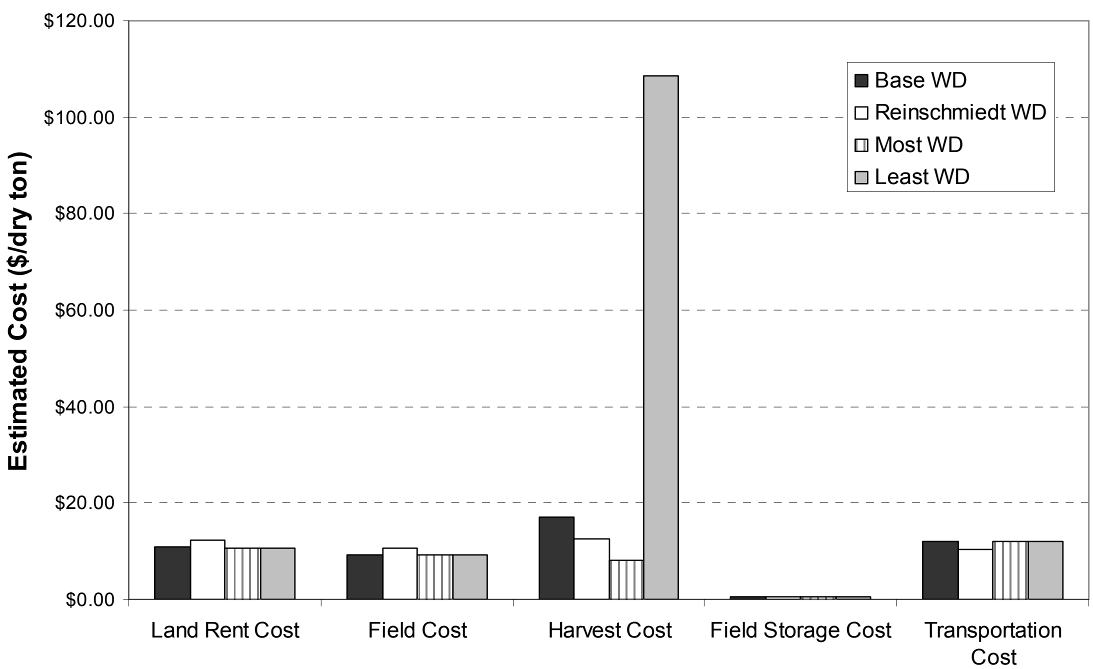

Figure 24. Estimated Land Rent Cost, Field Cost, Harvest Cost, Field Storage Cost, and Transportation Cost to Deliver a Flow of Switchgrass Feedstock to a 2,000 Dry Tons per Day Biorefinery for the Base WD, Reinschmiedt WD, Most WD, and Least WD Models

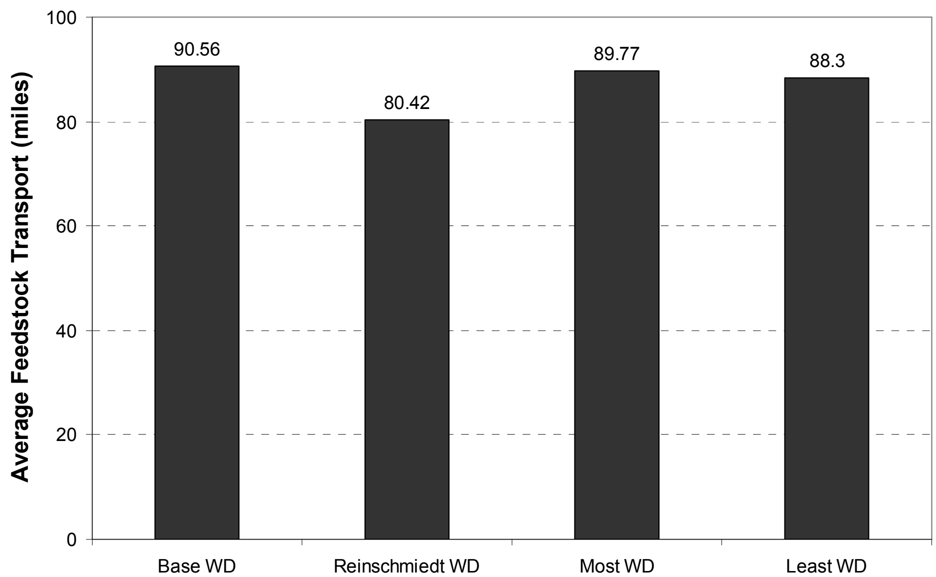

Figure 25. Estimated Average One-Way Distance to Transport Feedstock to a Biorefinery for the Base WD, Reinschmiedt WD, Most WD, and Least WD Models

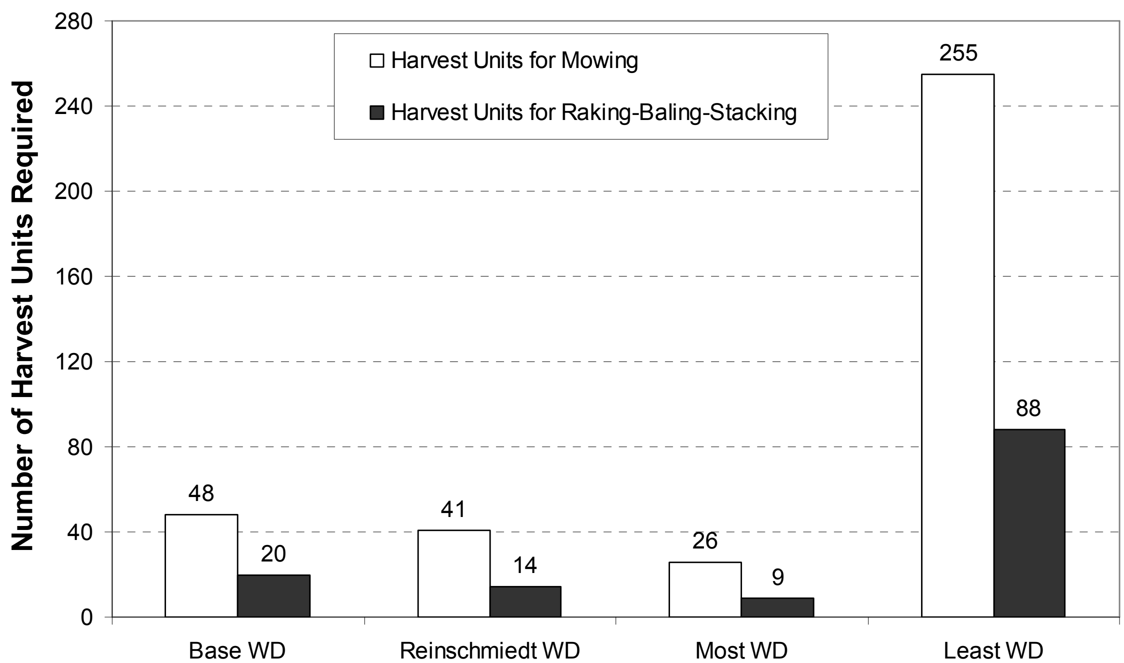

Figure 26. Estimated Number of Harvest Units for Mowing and Raking-Baling-Stacking for the Base WD, Reinschmiedt WD, Most WD, and Least WD Models

As described in table 14 and shown in figure 23, the estimated total cost to deliver a ton of feedstock to a 2,000 dry tons per day biorefinery is $49.7 in the Base WD model, $46.4 in the Reinschmiedt WD model, $40.4 in the Most WD model, and $141.0 in the Least WD model, respectively. The Least WD model has the highest total cost to deliver a ton of feedstock because it has substantially higher harvest cost ($108.5). These results indicate that the number of harvest days will be a critical parameter in determining the cost to deliver harvested switchgrass to a biorefinery.

In the model, the quantity of switchgrass harvested per month is restricted by the number of endogenously determined harvest units. The optimal number of harvest machines depends upon the number of workdays available in each month and daily capacity of a harvest unit. Since daily capacity of a harvest unit is constant, the number of workdays is a significant factor in determining the cost of delivered biomass. Fewer harvestable days requires more investment in harvest machines and harvest cost is, consequently, increased. On the contrary, more harvestable days result in a lower harvest cost.

These findings point out one advantage of a dedicated energy crop such as switchgrass that in Oklahoma could be harvested throughout an eight month time period, relative to crop residue, such as corn stover in the Corn Belt, which has a relatively narrow harvest window.

The estimated harvest cost is $17.00 per dry ton in the Base WD model and $12.60 ($4.40 less) per dry ton in the Reinschmiedt WD model, respectively. Therefore, Mapemba's harvest cost model using Reinschmiedt's workdays underestimates the harvest cost. Mapemba (2005) overestimated the number of number of baling days since he assumed that the number of mowing days and raking-baling-stacking days were identical.

With regard to field storage, all models have almost the same cost ($0.57 or $0.58 per dry ton). Land rent cost, field cost, and transportation cost are also very similar across all models except for the Reinschmiedt WD model (Figure 24). The costs of land rent and field cost for the Reinschmiedt WD model are greater than those for the other three models because with the Reinschmiedt estimate of harvestable days, the optimal biorefinery location shifts from Okmulgee to Canadian County. Estimated yields per acre are lower in West Central Oklahoma (Canadian County) and more acres must be harvested per year to provide 700,000 dry tons (2,000 tons per day times 350 days). That is, more acres would optimally be required for the Reinschmiedt WD model compared to the other three models because the expected yield of switchgrass in counties that provide feedstock to the Canadian County biorefinery (average 4.9 dry ton per acre) is less than the estimated yield in counties that would produce feedstock for delivery to a biorefinery located in Okmulgee County (average 5.6 dry ton per acre).

Transportation cost is lower in the Reinschmiedt WD model because estimated average feedstock transportation distance is shorter than that of the other three models (Table 14; Figure 25). A greater proportion of total land area is in cropland in the vicinity of the Canadian County relative to the Okmulgee County biorefinery location.

As the number of workdays increases from three days (Least WD model) to 30 days per month (Most WD model), the optimal number of harvest units decreases from 255 to 26 and from 88 to nine for the mowing operation and the raking-baling-stacking operation, respectively (Figure 26). These results are consistent with the harvest cost estimates. Fewer harvest days requires more harvest machines. Therefore, the average investment in harvest machines increases from $5.3 million for the Most WD model to $42.1 million ($36.8 million more) for the Least WD model. As reported in Table 14 and shown in figure 25, the optimal number of number of harvest units for mowing and raking-baling-stacking increases from 41 for the Reinschmiedt WD model to 48 for the Base WD model and from 14 to 20, respectively. Hence, under the Base WD model, a biorefinery that could process 2,000 dry tons per day would need 48 mowers, 60 balers, 60 rakes, 20 field transport stackers, and 168 tractors, which will require an average investment of about $11.3 million. Similarly, an estimated 41 mowers, 42 balers, 42 rakes, 14 field transport stackers, and 125 tractors are required under the Reinschmiedt WD model. The average investment in these harvest machines is about $8.2 million ($3.1 million more compared to the Base WD model). Therefore, a model using Reinschmiedt's estimates of workdays may have underestimated the investment required in harvest machines.

Figure 27 illustrates the estimated quantity of switchgrass harvested per month to provide a flow of feedstock to a 2,000 tons per day biorefinery for each of the four models. Tons of switchgrass harvested differ across months because monthly harvested tons are restricted by the number of harvest hours per day that varies with average day length, which exerts influence on daily capacity of harvest machines, and the number of harvest days that varies with weather conditions, which affects the number of harvest units, and yield adjustment factor (Mapemba 2005). More than 300,000 tons (Table 15) would be harvested in the month of July, August, and September: 343,220 tons (48% of

Table 15. Estimated Quantity of Switchgrass Harvested per Month for the Base WD, Reinschmiedt WD, Most WD, and Least WD Models to Provide a Flow of Feedstock to a 2,000 Tons per Day Biorefinery

		Jan	Feb	Jul	Aug	Sep	Oct	Nov	Dec	Total
Base WD	ton	85,996	92,081	135,680	119,700	87,840	39,960	69,888	85,536	716,681
	%[a]	(12.0)	(12.8)	(18.9)	(16.7)	(12.3)	(5.6)	(9.8)	(11.9)	(100.0)
	%[b]	(-36.6)	(-32.1)	(0.0)	(-11.8)	(-35.3)	(-70.5)	(-48.5)	(-37.0)	
Reinschmiedt WD	ton	89,928	84,525	112,756	107,531	82,650	73,427	75,847	88,220	711,881
	%[a]	(12.2)	(11.9)	(15.8)	(15.1)	(11.6)	(10.3)	(10.7)	(12.4)	(100.0)
	%[b]	(-22.9)	(-25.0)	(0.0)	(-4.6)	(-26.7)	(-34.9)	(-32.7)	(-21.8)	
Most WD	ton	79,560	71,153	113,880	106,860	98,280	88,920	81,120	77,220	716,993
	%[a]	(11.1)	(9.9)	(15.9)	(14.9)	(13.7)	(12.4)	(11.3)	(10.8)	(100.0)
	%[b]	(-30.1)	(-37.5)	(0.0)	(-6.2)	(-13.7)	(-21.9)	(-28.8)	(-32.2)	
Least WD	ton	78,030	83,053	111,690	104,805	96,390	87,210	79,560	75,735	716,473
	%[a]	(10.9)	(11.6)	(15.6)	(14.6)	(13.5)	(12.2)	(11.1)	(10.6)	(100.0)
	%[b]	(-30.1)	(-25.6)	(0.0)	(-6.2)	(-13.7)	(-21.9)	(-28.8)	(-32.2)	

[a] The values in parentheses are percentage of total harvested tons for a year.

[b] The values in parentheses are percentage changes from the number of tons harvested in month of July.

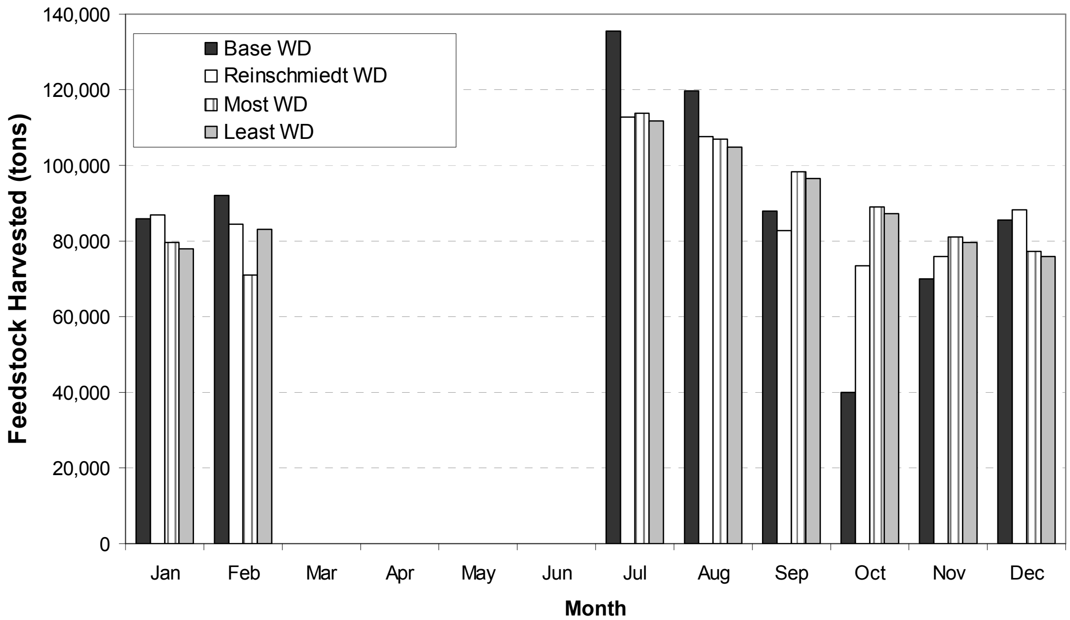

Figure 27. Estimated Quantity of Switchgrass Harvested per Month for the Base WD, Reinschmiedt WD, Most WD, and Least WD Models to Provide a Flow of Feedstock to a 2,000 Tons per Day Biorefinery

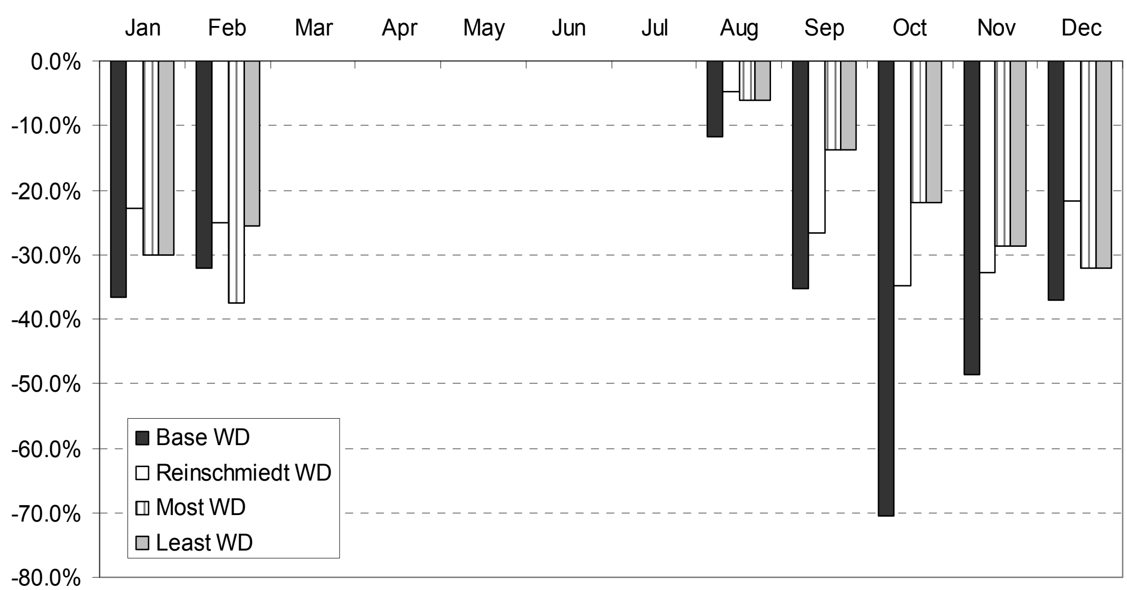

Figure 28. The Percentage Changes from the Estimated Quantity of Switchgrass Harvested in July for the Base WD, Reinschmiedt WD, Most WD, and Least WD Models

total harvested tons) for Base WD model, 302,937 tons (43%) for the Reinschmiedt WD model, 319,020 tons (45%) for the Most WD model, and 312,885 tons (44%) for the Least WD model. These results are consistent with the highest level of the yield adjustment factor (YAD) for switchgrass (see Table 10 in Chapter 4).

The YAD is equal to one in July, August, and September. Figure 28 includes percentage changes from the estimated quantity of switchgrass harvested in July. The absolute values of percentage changes from the base month yield increase steadily until the month of February for the Most WD model (except January) and until the month of December for the Least WD model. In addition, both the Most WD model and the Least WD model have the same value of percentage changes in each month except for February (e.g., –6% for August in both the Most WD and the Least WD model). Hence, the Most WD model and the Least WD model have the same declining pattern of the number of tons harvested. This is because the proportion of the number of harvest days available in each month is uniform. In other words, because the Least WD has three days and the Most WD model has 30 days in each month, regardless of weather conditions, the differences in harvested tons across months in both of these models is a consequence of the yield adjustment (YAD) factor.

The YAD factor starts declining in October and continues to decline by 0.05 in each month until February. On the contrary, the Base WD model and the Reinschmiedt WD model have the same pattern of percentage changes: the absolute values of percentage changes of each month grow until October and then decline until February. The quantity of feedstock harvested in October is relatively small. October harvest is expected to be 39,960 tons (5.6% of total harvested tons) in the Base WD model and

73,427 tons (10.3%) in the Reinschmiedt WD model. This is because October has a relatively small number of workdays.[12] Thus, monthly harvested tons in the Base WD model are a function of both the yield adjustment factor and weather conditions. The Reinschmiedt WD model that does not consider the influence of weather on moisture content of cut grasses is likely to overestimate the number of raking-baling-stacking days and underestimate the investment required in harvest machines necessary to provide sufficient feedstock to a biorefinery.

Figure 29 includes the total number of switchgrass harvested acres in each region. In the Base WD, Most WD, and Least WD models most of the harvested acres are distributed across the East Central and Northeast (76% of total harvest acres), while estimated harvested acres for the Reinschmiedt WD model are concentrated in the Central region (56%). This is because the optimal biorefinery is expected to be located in Okmulgee County (East Central) for the Base WD, Most WD, and Least WD models and in Canadian County (Central) for the Reinschmiedt WD model.

Figure 31 contains an illustrated Oklahoma map of the estimated number of acres, the quantity of switchgrass harvested, and yield per acre of each county providing a flow of feedstock to a 2,000 tons per day biorefinery located in Okmulgee County. These estimates are based upon results from the Base WD model. Figure 32 includes results for the biorefinery located in Canadian County based upon results from Reinschmiedt WD model.

[12] The average percentage of the number of workdays for mowing and raking-baling-stacking in October used in the Base WD model is 12% of the total number of mowing days and 6% of the total number of raking-baling-stacking days during harvest season (July-February of following next year) of regions producing biomass, respectively, and in the Reinschmiedt WD model, the number of workdays is 11% regardless of type of harvesting operation.

Figure 30 includes the estimated quantity of infield storage for a 2,000 dry tons per day biorefinery from each of the four models. Replenishment of storage reserves begins with the first permissible harvest month of July. Field inventory storage increases more gradually from July through February of following year. When harvest stops at the end of February, field inventory storage declines steadily until harvest may be resumed the following July. From March through June, biorefinery needs must be fulfilled exclusively from feedstock in storage.

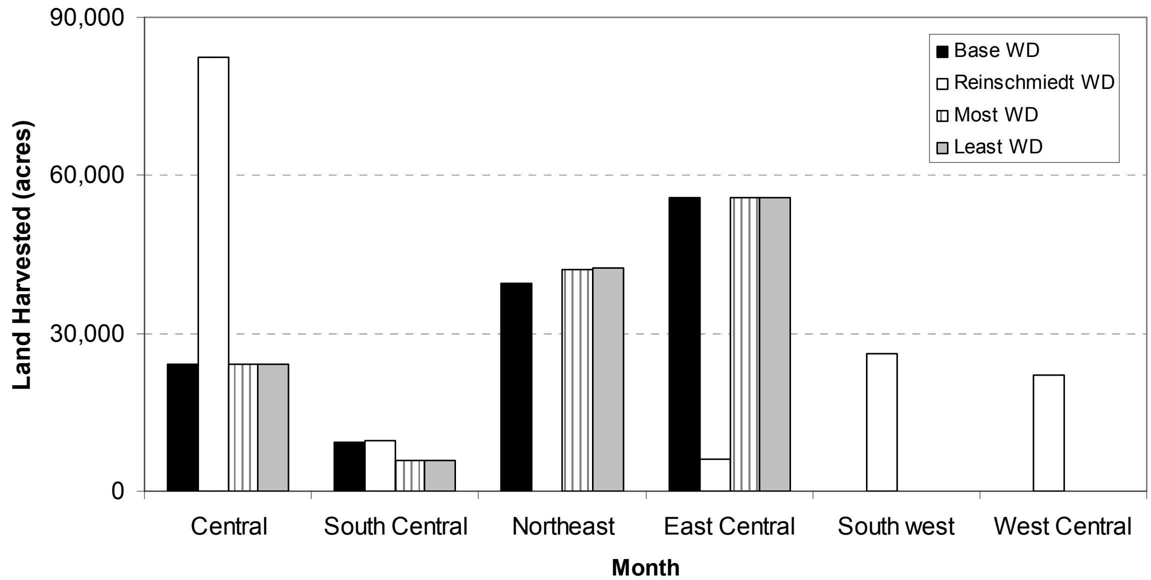

Figure 29. Estimated Total Number of Acres Harvested in Each Region for the Base WD, Reinschmiedt WD, Most WD, and Least WD Models to Provide a Flow of Feedstock to a 2,000 Tons per Day Biorefinery

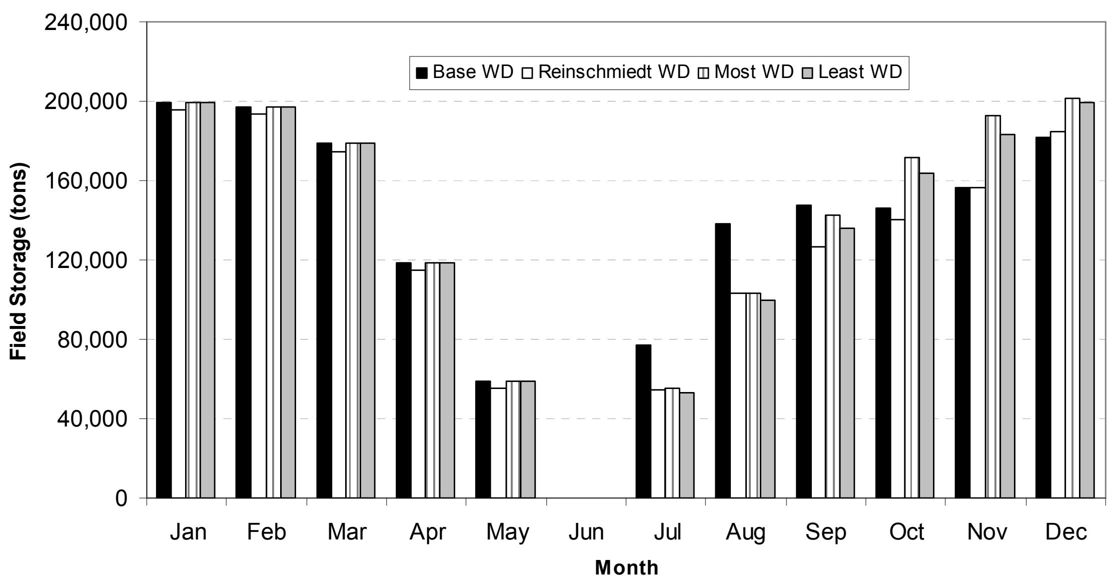

Figure 30. Estimated Quantity of Feedstock Stored Per Month in the Field for a 2,000 Tons per Day Biorefinery for the Base WD, Reinschmiedt WD, Most WD, and Least WD Models

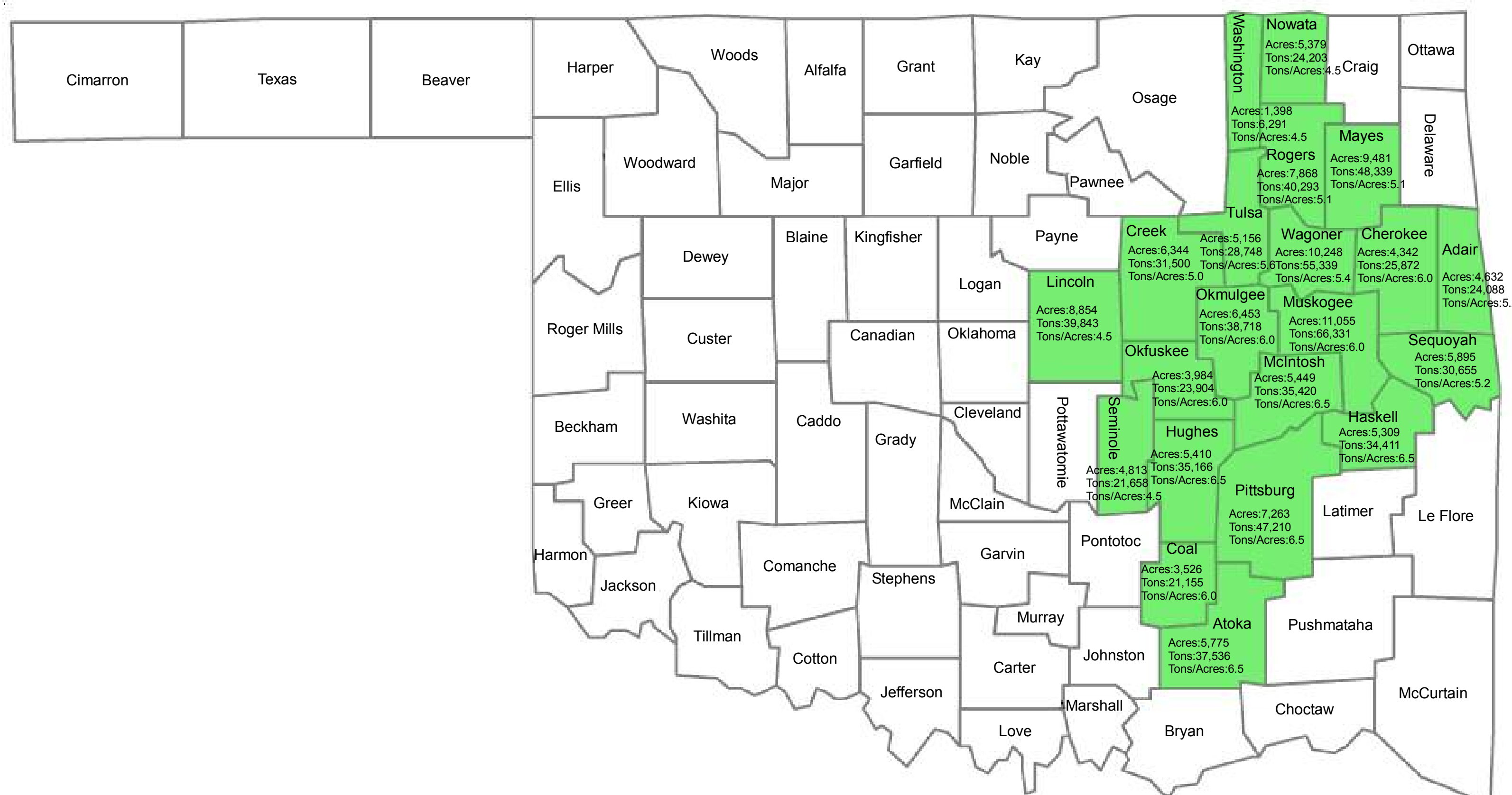

Figure 31. Map of Oklahoma Showing the Number of Acres, Harvested Tons, and Yield per Acre of Counties Harvesting Switchgrass Based upon the Results from the Base WD Model

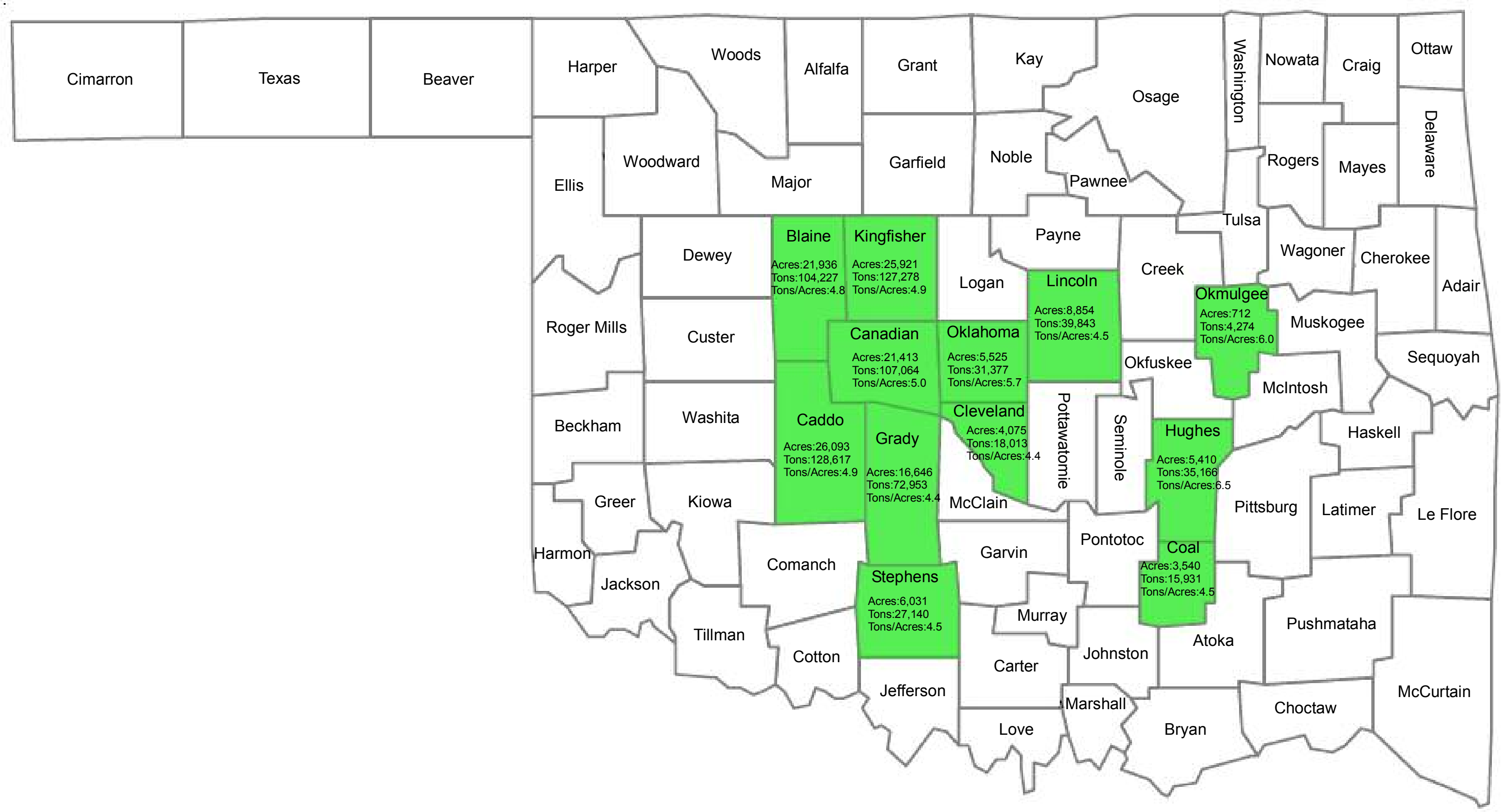

Figure 32. Map of Oklahoma Showing the Number of Acres, Harvested Tons, and Yield per Acre of Counties Harvesting Switchgrass Based upon the Results from the Reinschmiedt WD Model

Comparisons among Different Biorefinery Sizes for the Base Model

In this study the Base WD model is considered as a base model. Alternative models were differentiated by biorefinery sizes based upon daily capacity for processing feedstock (i.e., 1,000, 2,000, 3,000, and 4,000 dry tons per day). Hence, a 1,000 dry tons per day biorefinery means that this plant has capacity to process a maximum of 1,000 dry tons of feedstock per day. The biorefinery size used in the base model is assumed to be 2,000 dry tons per day. Table 16 includes a summary of results from each of four different biorefinery sizes for plants located in both Okmulgee county and Canadian county.[13]

In general, there is an expectation that an increase in plant size is accompanied with an increase in harvested acres, harvested feedstock, harvest units, and average distance to transport feedstock. Therefore, as the size of the biorefinery is increased from 1,000 to 4,000 dry tons per day, the expected cost to deliver a ton increases. For the biorefineries located in Okmulgee and Canadian County the estimated total cost to deliver a ton of feedstock to a biorefinery increases from about $48 to $53 and $50 to $53, respectively. Close examination reveals that transportation cost increases gradually as the biorefinery size increases within the same plant location. For instance, the average one-way distance to transport feedstock from the field to the biorefinery located in Okmulgee is 73 miles, 91 miles, 99 miles, and 115 miles and costs corresponding to each of these distances are about $10, $12, $14, and $15 per ton for the 1,000, 2,000, 3,000, and 4,000

[13] Okmulgee and Canadian county were selected as an optimal plant location. As a result of pre-estimation, Okmulgee County was selected in both 1,000 and 2,000 dry tons per day biorefineries; however, Canadian County was selected for both the 3,000 and 4,000 dry tons per day biorefineries.

Table 16. Comparison of Results for Estimated Costs, Number of Harvest Units, Average Investment in Harvest Machines, and Acres and Tons Harvested to Provide a Flow of Switchgrass Feedstock to a 1,000, 2,000, 3,000, and 4,000 Dry Tons per Day Biorefinery

	Model Comparison							
Capacity of biorefinery	1000 tons*	2000 tons*	3000 tons	4000 tons	1000 tons	2000 tons	3000 tons*	4000 tons*
Plant Location	Okmulgee				Canadian			
Costs								
Land rent cost ($/ton)	10.87	10.77	10.94	11.31	12.45	12.40	12.56	12.57
Field cost ($/ton)[a]	9.31	9.23	9.37	9.69	10.66	10.62	10.76	10.77
Harvest cost ($/ton)	17.04	17.04	16.88	16.68	17.05	16.48	16.24	16.20
Field Storage cost ($/ton)	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58
Transportation cost ($/ton)	10.16	12.07	13.70	14.94	8.76	10.45	11.37	12.69
Total cost of delivered feedstock ($/ton)	47.96	49.68	51.47	53.19	49.50	50.53	51.50	52.82
Other results								
Harvest units for mowing (number)[b]	24	48	77	103	24	49	73	99
Harvest units for raking-baling-staking (number)[c]	10	20	29	38	10	19	28	37
Average investment in harvest machines ($,000)	5,641	11,281	16,675	21,940	5,641	10,863	16,042	21,307
Average distance hauled (miles)	73	91	99	115	65	77	87	100
Harvest acres	64,934	128,633	195,873	269,835	74,275	147,884	224,606	299,878
Total biomass harvested (tons)	358,324	716,681	1,074,159	1,431,829	358,009	715,710	1,073,365	1,430,948

[a] Field cost includes amortized establishment, maintenance, and fertilizer costs.
[b] A harvest unit for mowing includes one mower, one tractor, and one worker.
[c] A harvest unit for raking-baling-stacking includes three rakes, three balers, one transport stacker, six tractors, and seven workers.
[d.] * indicates an optimal capacity of biorefinery.

dry tons per day biorefinery, respectively. These variations follow from the change in arces to harvest. Hence, a larger capacity plant requires more acres to harvest and longer distances to transport.

As described in Table 16, land rental cost for a biorefinery located in Okmulgee County (average $10.97 per ton) is lower than that of Canadian County (average $12.49 per ton). For the field cost, Okmulgee County (average $9.40 per ton) is also lower than Canadian County (average $10.70 per ton). Harvest cost is estimated to average $16.91 per ton in Okmulgee County and $16.49 ($0.42 less) per ton in Canadian County. However, transportation cost for a biorefinery located in Okmulgee County (average $12.78 per ton) is higher than that of Canadian County (average $10.82 per ton). These results are from the trade-off between estimated switchgrass yield per acre, estimated transportation distances, and differences in harvest days. Estimated yields per acre are relatively lower near the Canadian County location than near the Okmulgee County location and more acres are required. Thus, land rental cost and field cost for a biorefinery located in Canadian County is relatively higher than that of Okmulgee County. However; since more cropland is concentrated near the Canadian County location, average transportation distance is shorter and transportation cost for a biorefinery located in Canadian County is relatively lower. Since on average there are a few more harvest days per month near the Canadian County location, there is a slight difference in harvest cost between Canadian County and Okmulgee County.

To supply feedstock to a biorefinery with processing capacity of 1,000, 2,000, 3,000, or 4,000 dry tons per day located in Okmulgee County, 11 counties, 21 counties, 31 counties, or 41 counties of Oklahoma’s 77 counties were optimally selected to produce switchgrass, respectively. Likewise, for a biorefinery located in Canadian County, 5 counties, 12 counties, 21 counties, or 27 counties were selected to provide 1,000, 2,000, 3,000 or 4,000 dry ton per day, respectively. Figures 43 through 50 include Oklahoma maps of the estimated number of acres, the quantity of switchgrass harvested, and yield per acre of each county selected to provide feedstock to a 1,000, 2,000, 3,000, and 4,000 tons per day biorefinery located in Okmulgee County and Canadian County. Figures 33 through 42 provide detailed results for four different sizes of biorefinery located in Okmulgee and Canadian County.

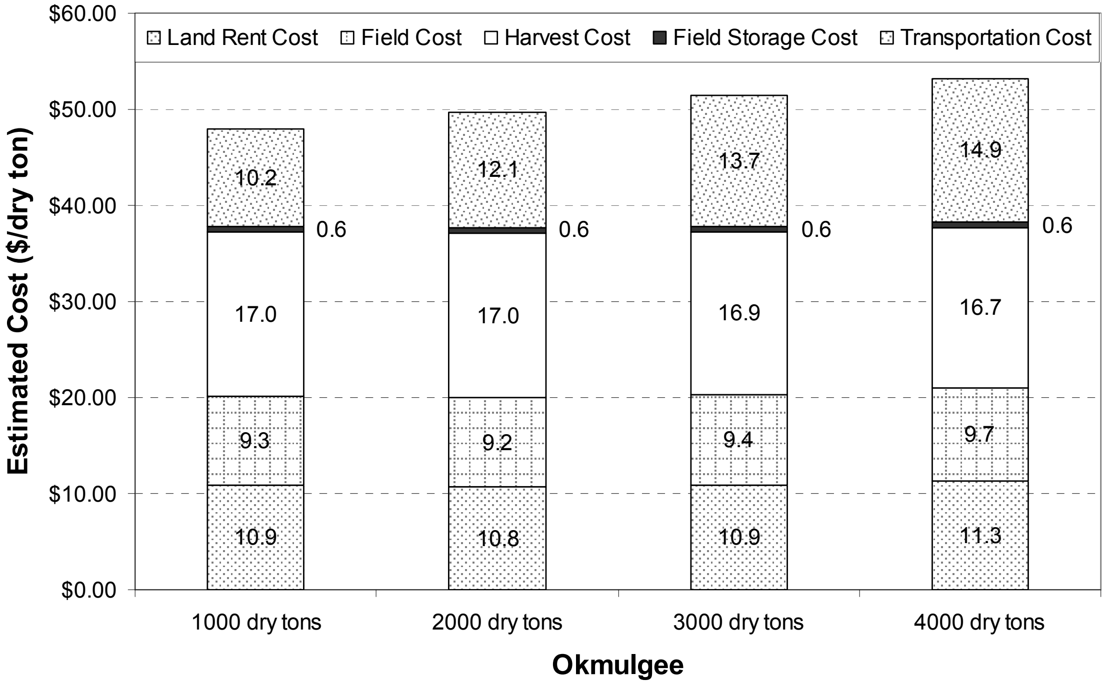

Figure 33. Estimated Cost to Deliver a Flow of Switchgrass Feedstock to a Biorefinery Located in Okmulgee County

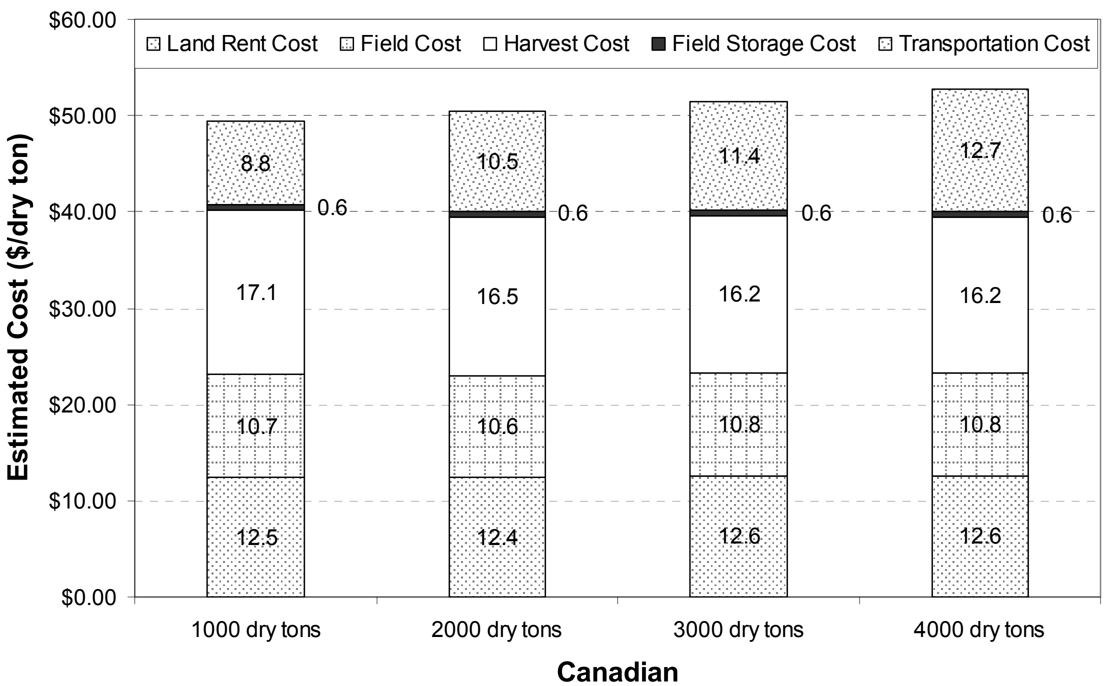

Figure 34. Estimated Cost to Deliver a Flow of Switchgrass Feedstock to a Biorefinery Located in Canadian County

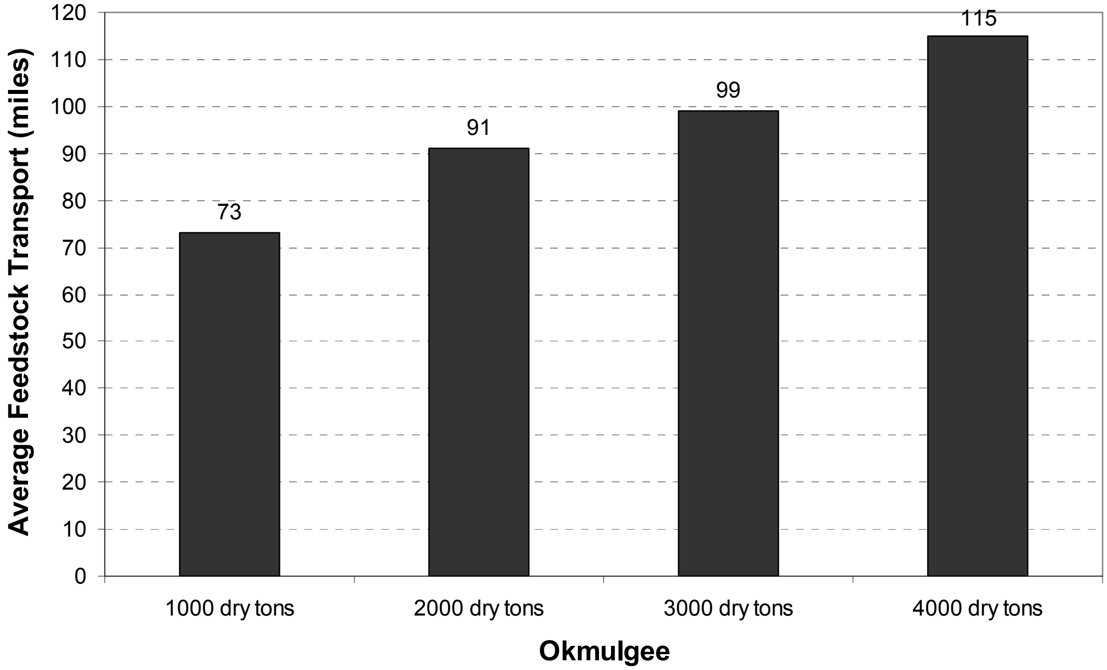

Figure 35. Estimated Average One-Way Distance to Transport Feedstock to a Biorefinery Located in Okmulgee County

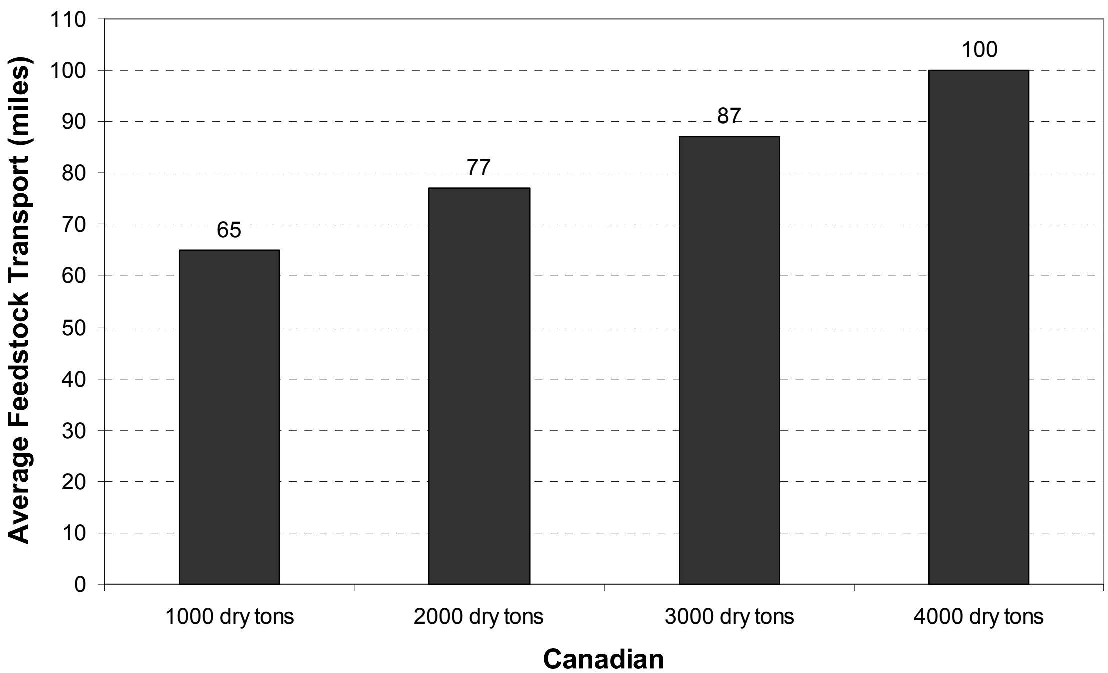

Figure 36. Estimated Average One-Way Distance to Transport Feedstock to a Biorefinery Located in Canadian County

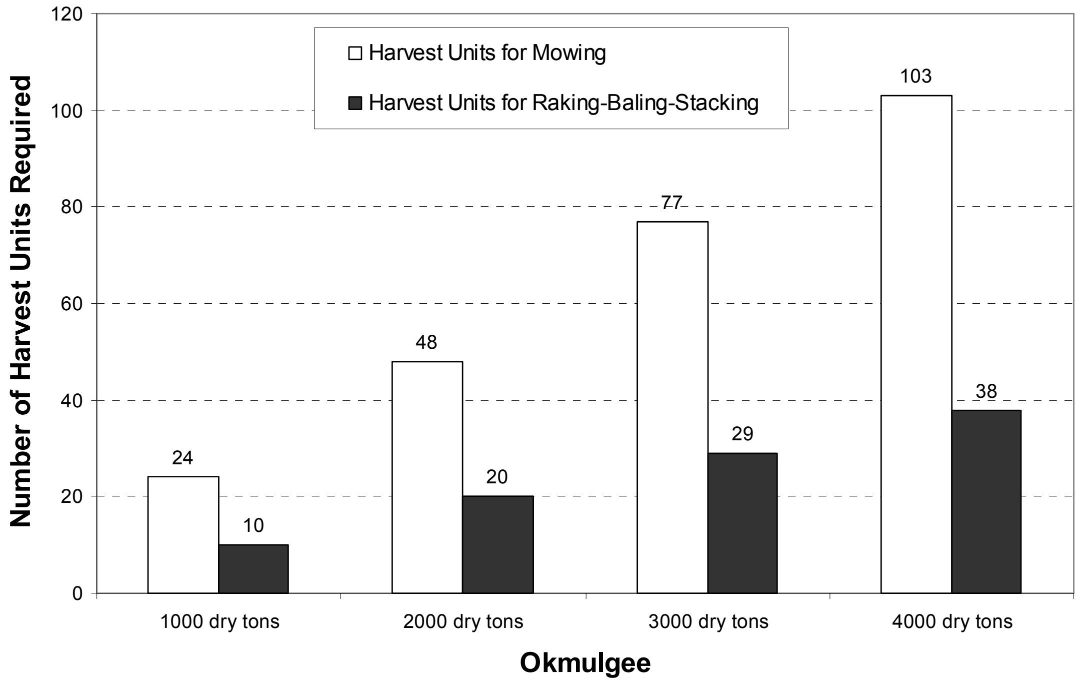

Figure 37. Estimated Number of Harvest Units for Mowing and Raking-Baling-Stacking for a Biorefinery Located in Okmulgee County

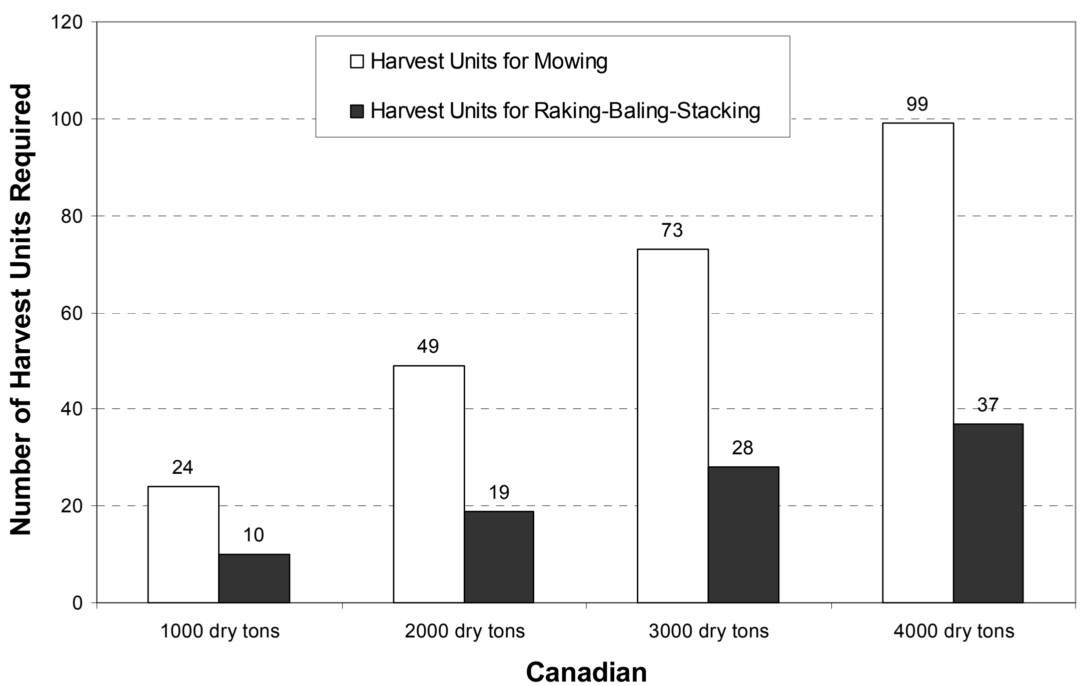

Figure 38. Estimated Number of Harvest Units for Mowing and Raking-Baling-Stacking for a Biorefinery Located in Canadian County

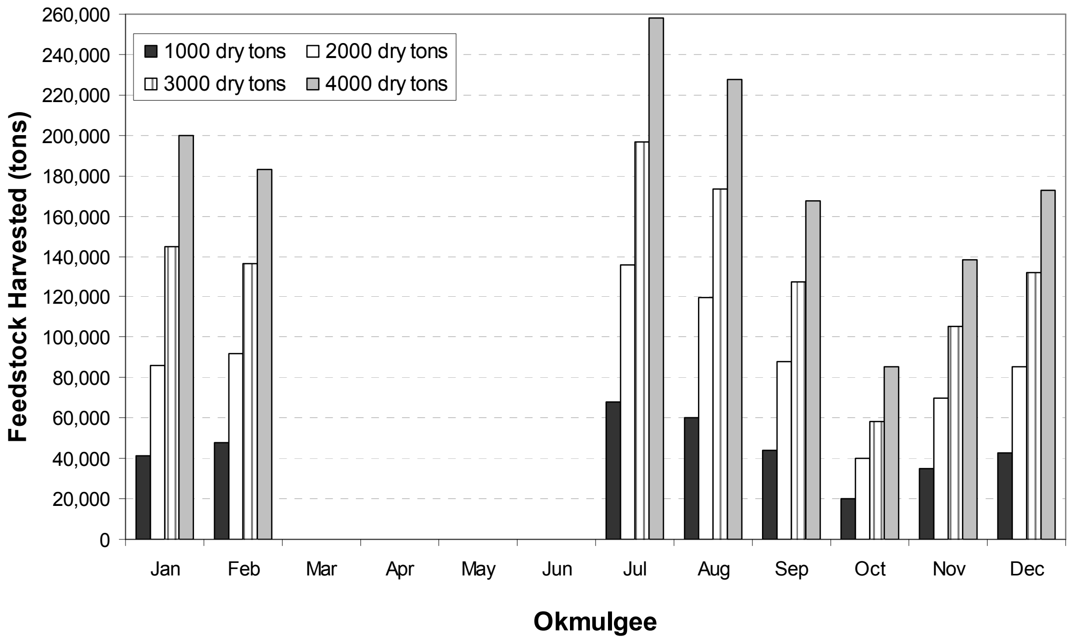

Figure 39. Estimated Quantity of Switchgrass Harvested per Month to Provide a Flow of Feedstock to a 1,000, 2,000, 3,000, and 4,000 Tons per Day Biorefinery Located in Okmulgee County

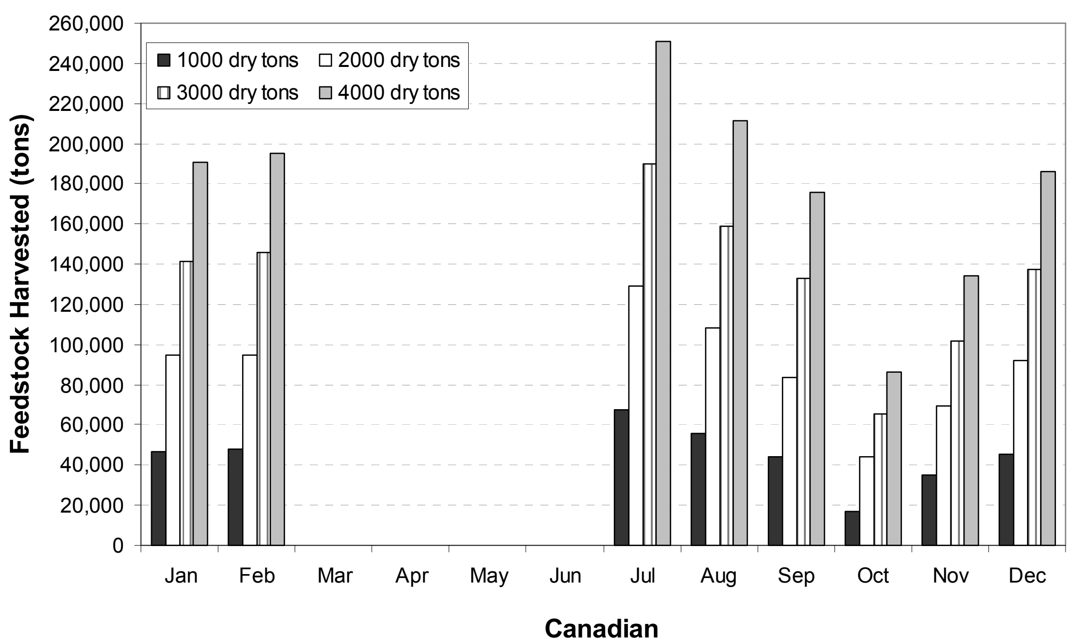

Figure 40. Estimated Quantity of Switchgrass Harvested per Month to Provide a Flow of Feedstock to a 1,000, 2,000, 3,000, and 4,000 Tons per Day Biorefinery Located in Canadian County

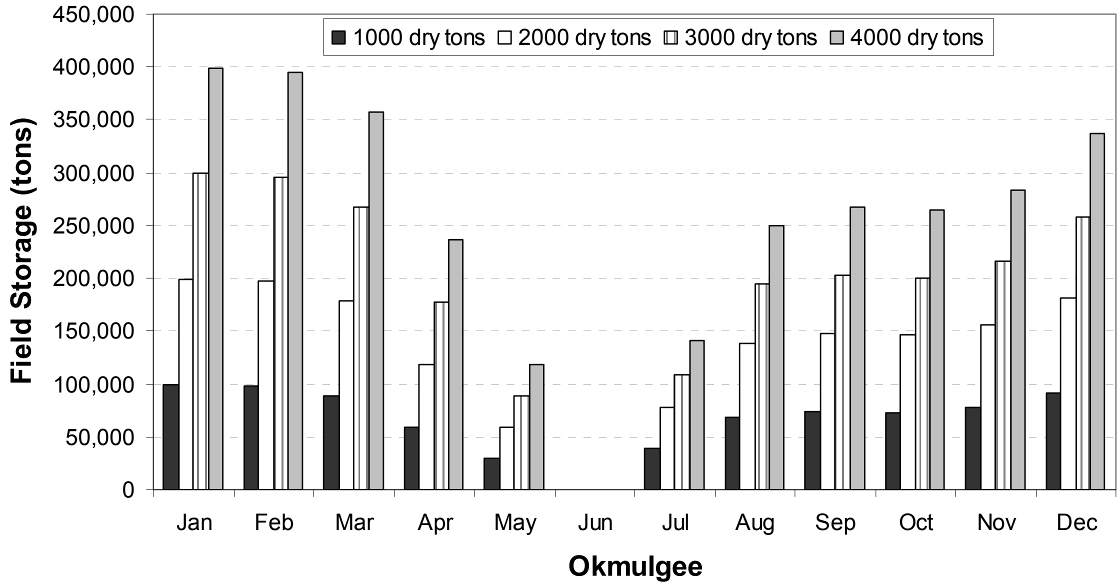

Figure 41. Estimated Quantity of Feedstock Stored per Month in the Field for a 1,000, 2,000, 3,000, and 4,000 Tons per Day Biorefinery Located in Okmulgee County

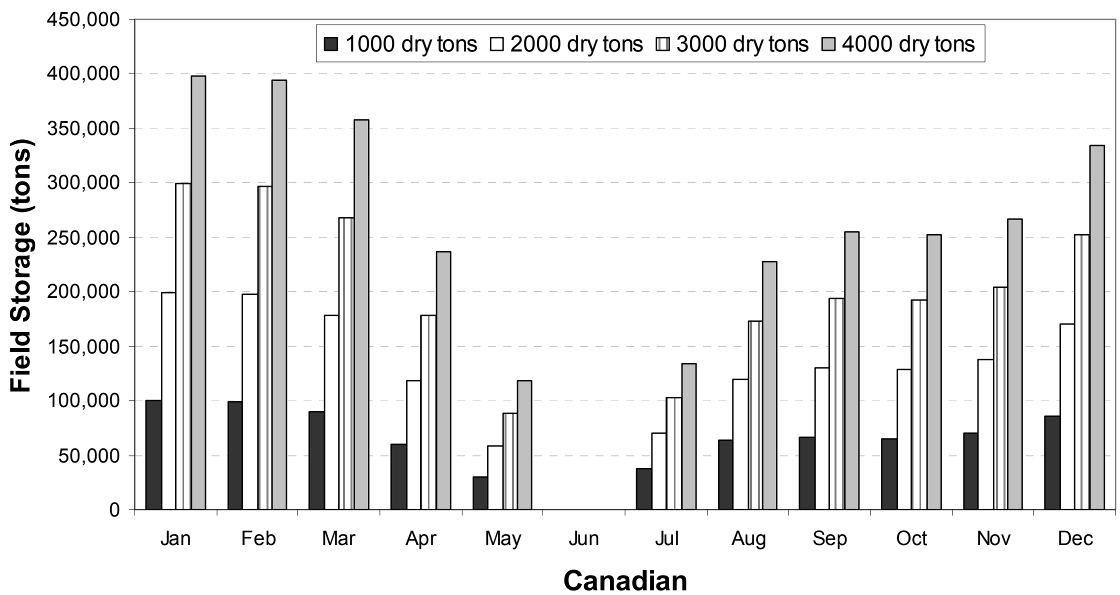

Figure 42. Estimated Quantity of Feedstock Stored per Month in the Field for a 1,000, 2,000, 3,000, and 4,000 Tons per Day Biorefinery Located in Canadian County

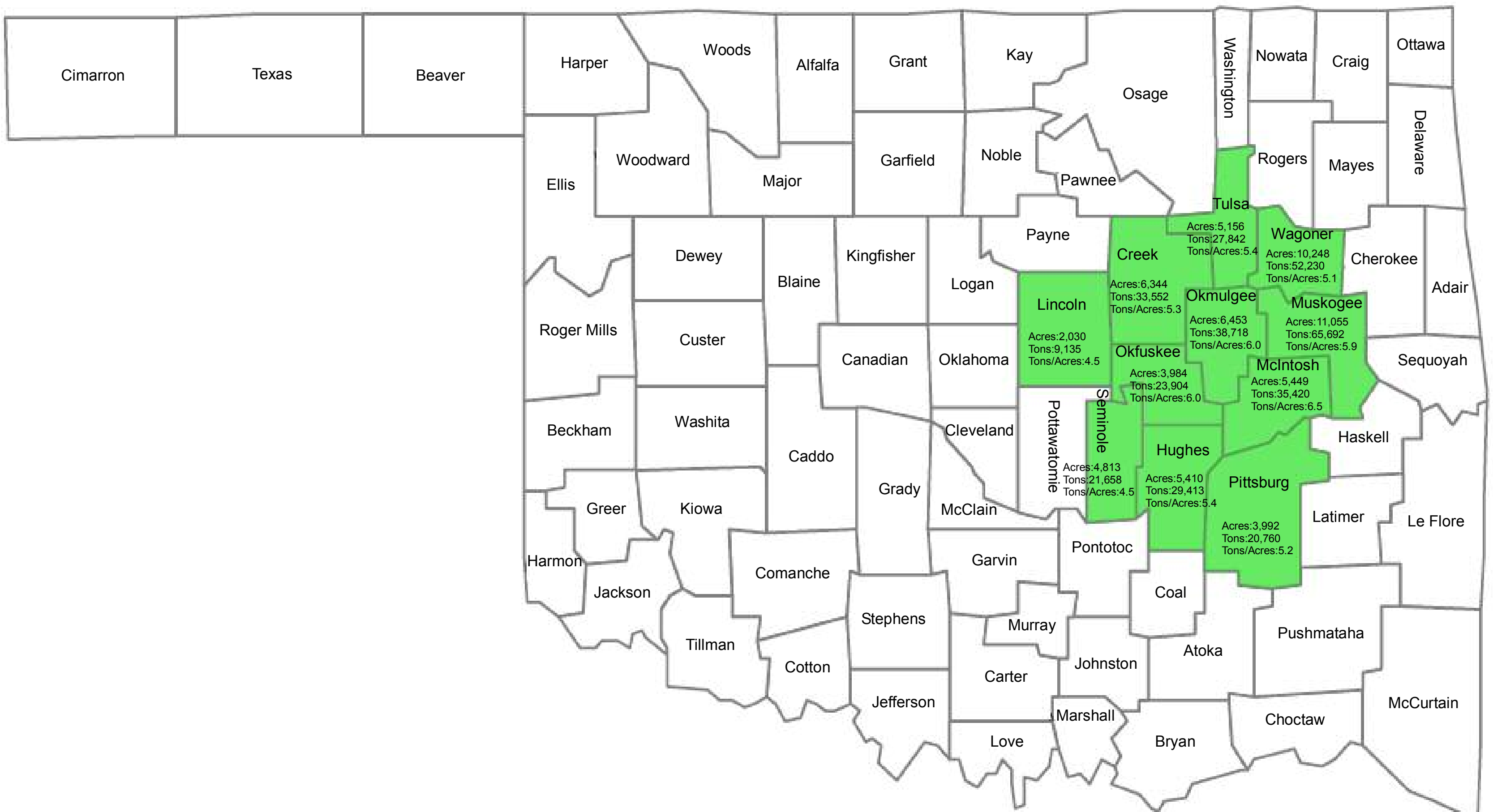

Figure 43. Map of Oklahoma Showing the Number of Acres, Harvested Tons, and Yield per Acre of Counties Harvesting Switchgrass for 1,000 Dry Tons per Day Biorefinery Located in Okmulgee County

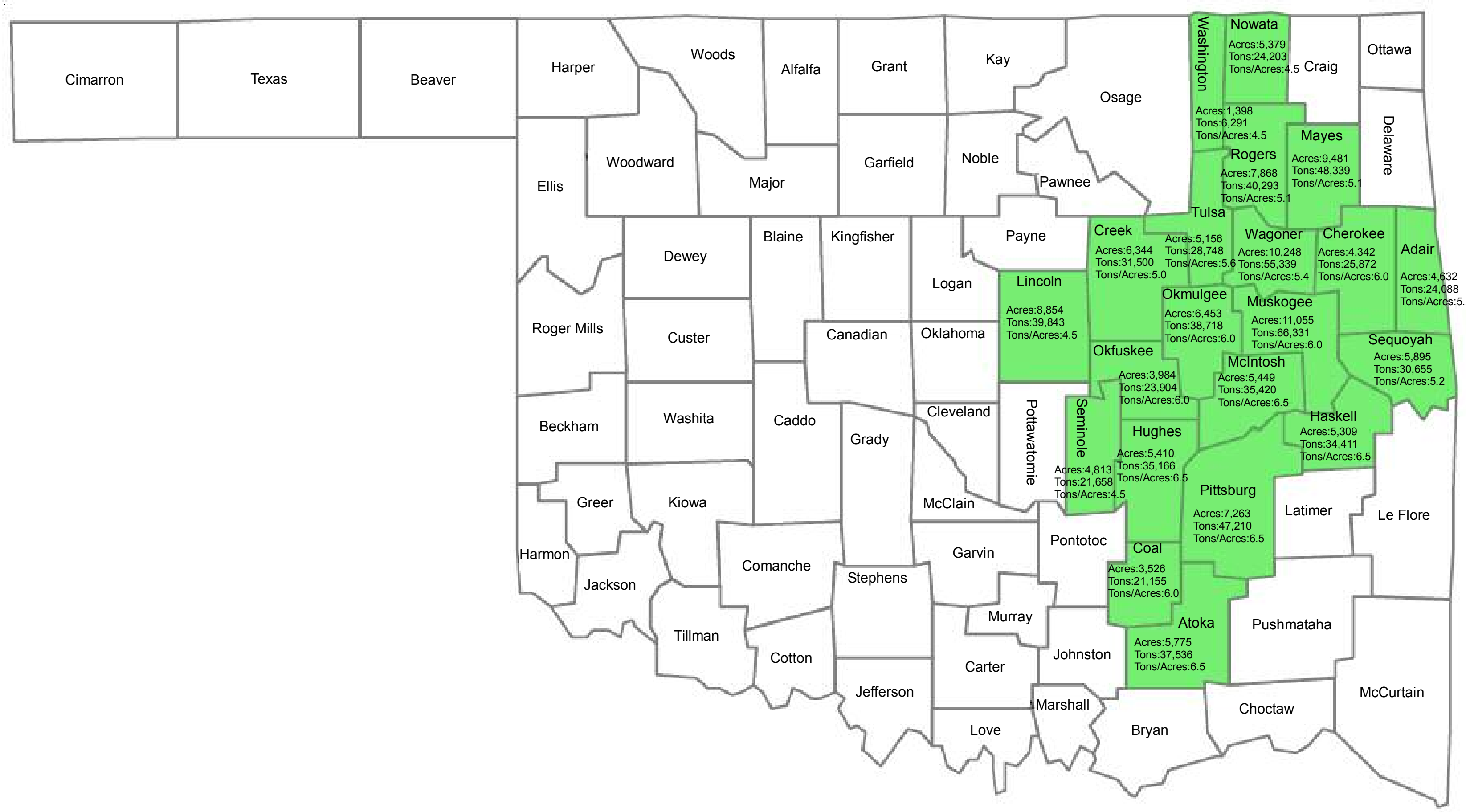

Figure 44. Map of Oklahoma Showing the Number of Acres, Harvested Tons, and Yield per Acre of Counties Harvesting Switchgrass for 2,000 Dry Tons per Day Biorefinery Located in Okmulgee County

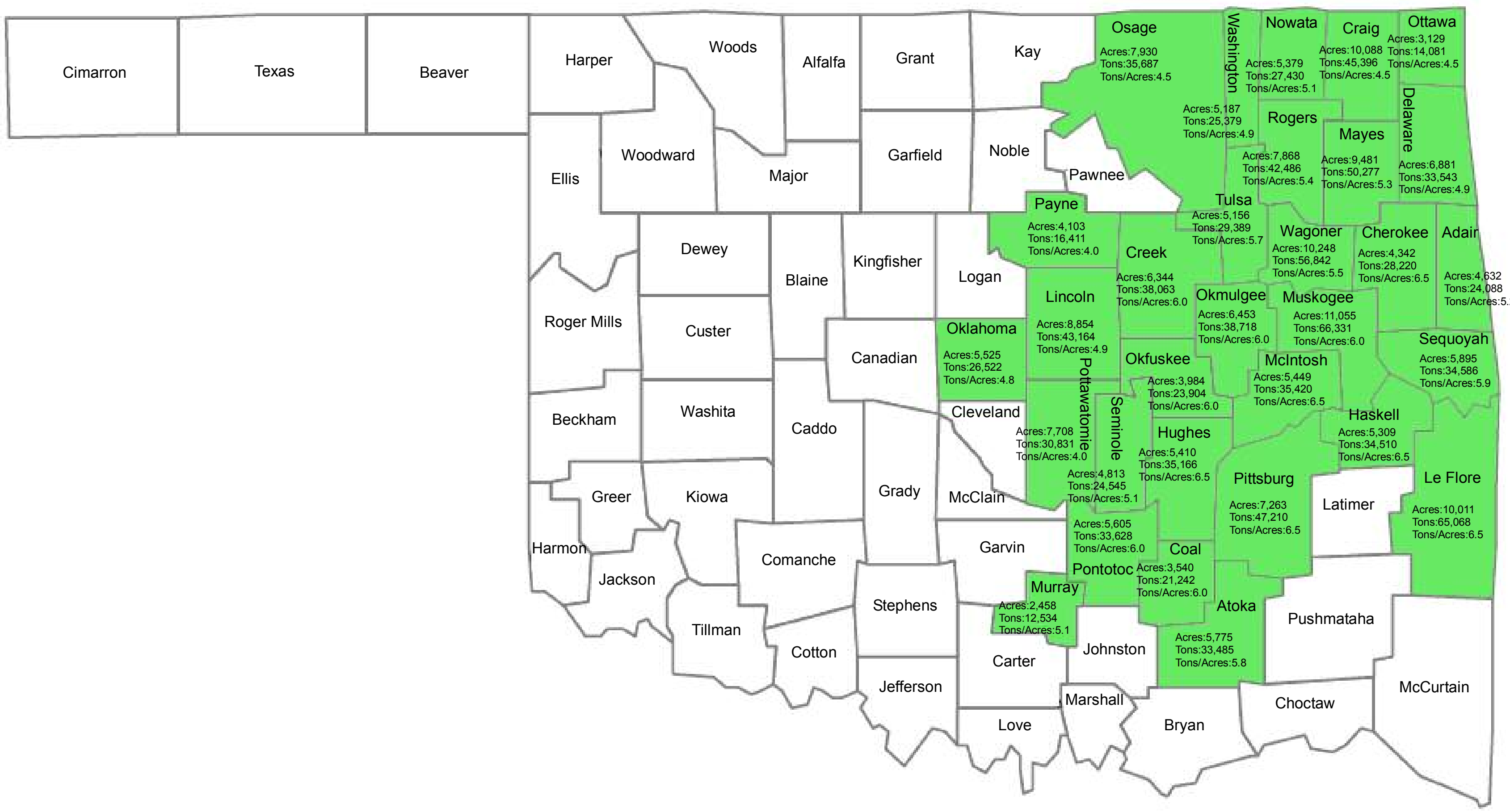

Figure 45. Map of Oklahoma Showing the Number of Acres, Harvested Tons, and Yield per Acre of Counties Harvesting Switchgrass for 3,000 Dry Tons per Day Biorefinery Located in Okmulgee County

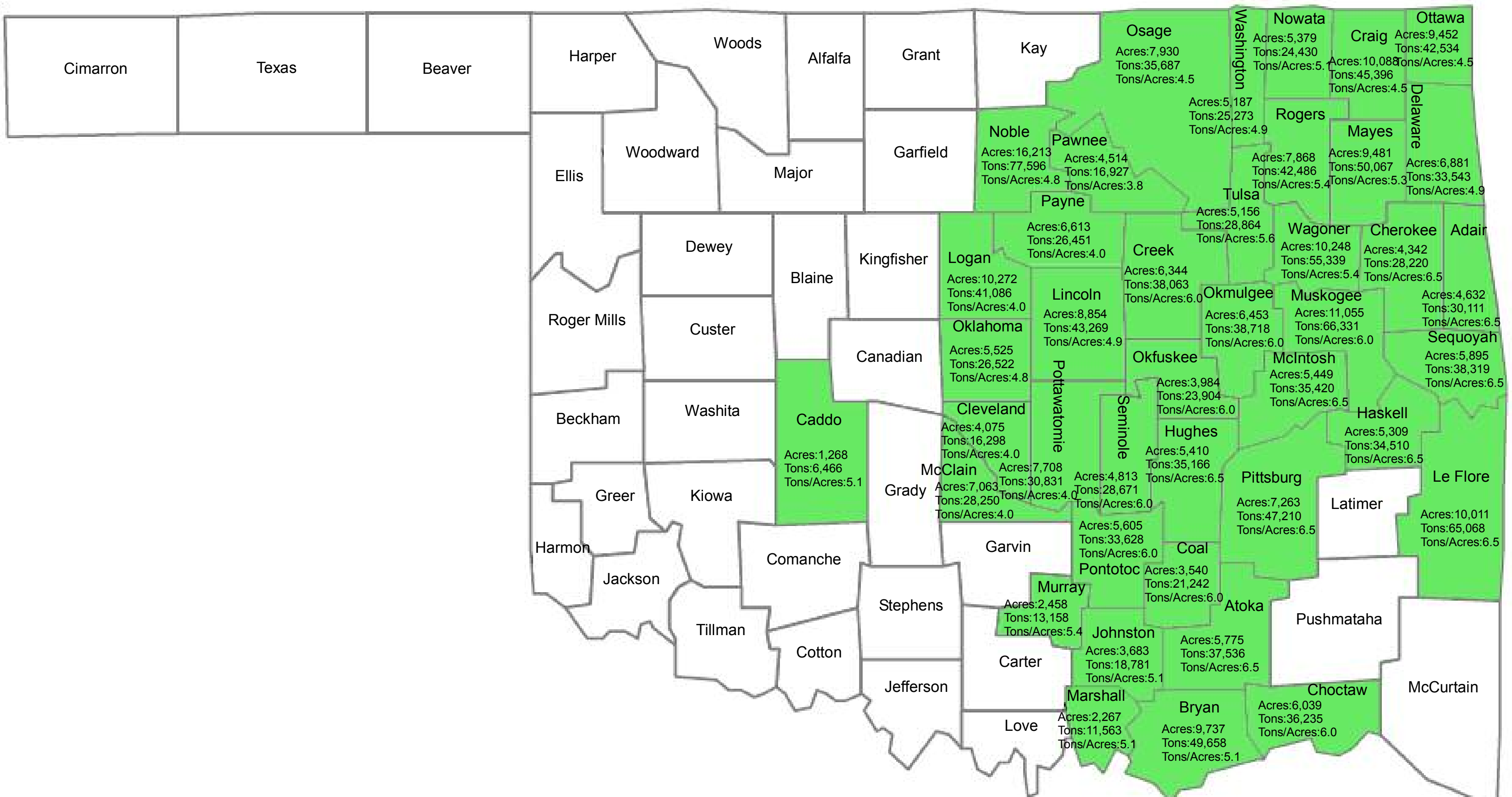

Figure 46. Map of Oklahoma Showing the Number of Acres, Harvested Tons, and Yield per Acre of Counties Harvesting Switchgrass for 4,000 Dry Tons per Day Biorefinery Located in Okmulgee County

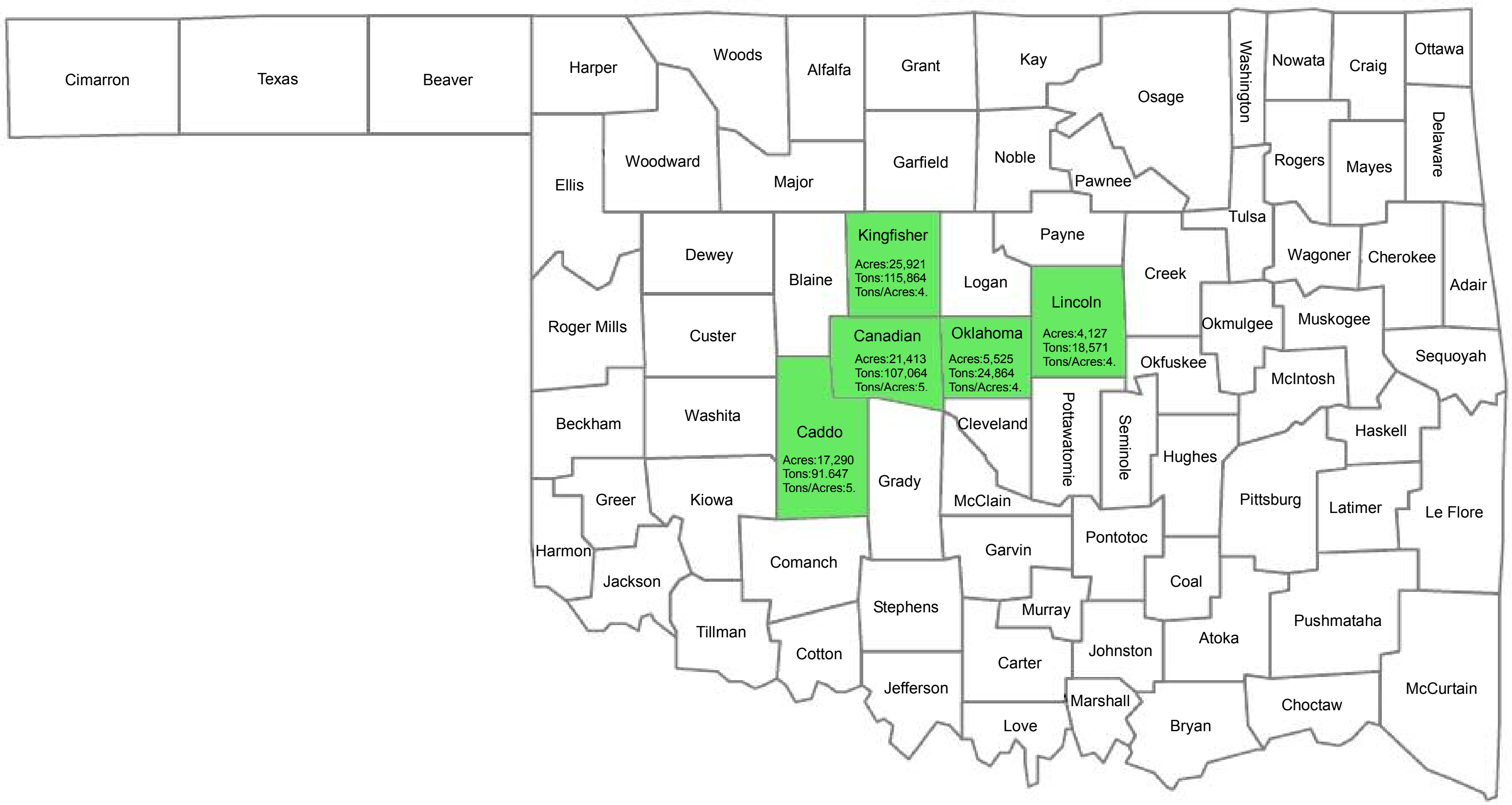

Figure 47. Map of Oklahoma Showing the Number of Acres, Harvested Tons, and Yield per Acre of Counties Harvesting Switchgrass for 1,000 Dry Tons per Day Biorefinery Located in Canadian County

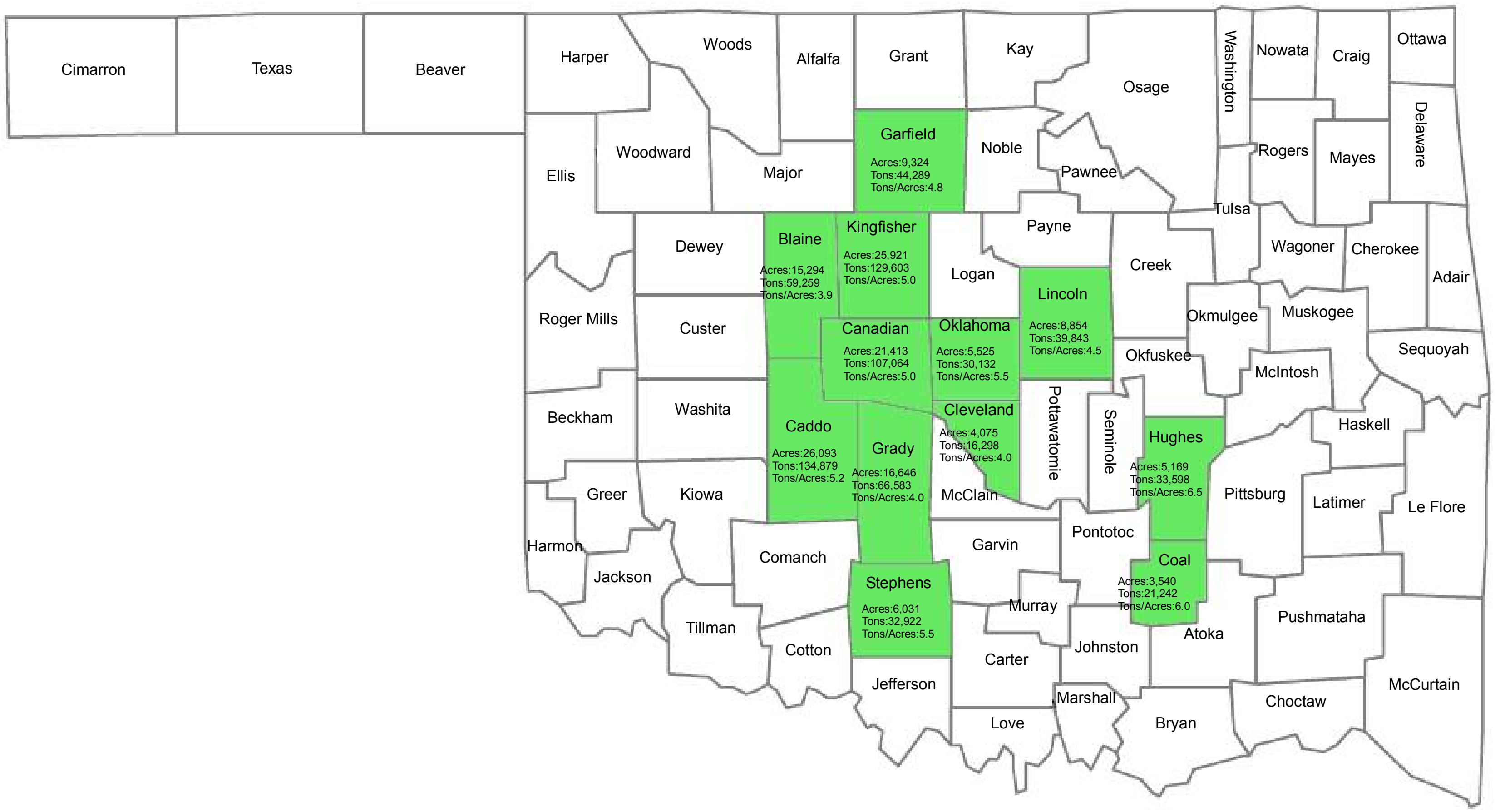

Figure 48. Map of Oklahoma Showing the Number of Acres, Harvested Tons, and Yield per Acre of Counties Harvesting Switchgrass for 2,000 Dry Tons per Day Biorefinery Located in Canadian County

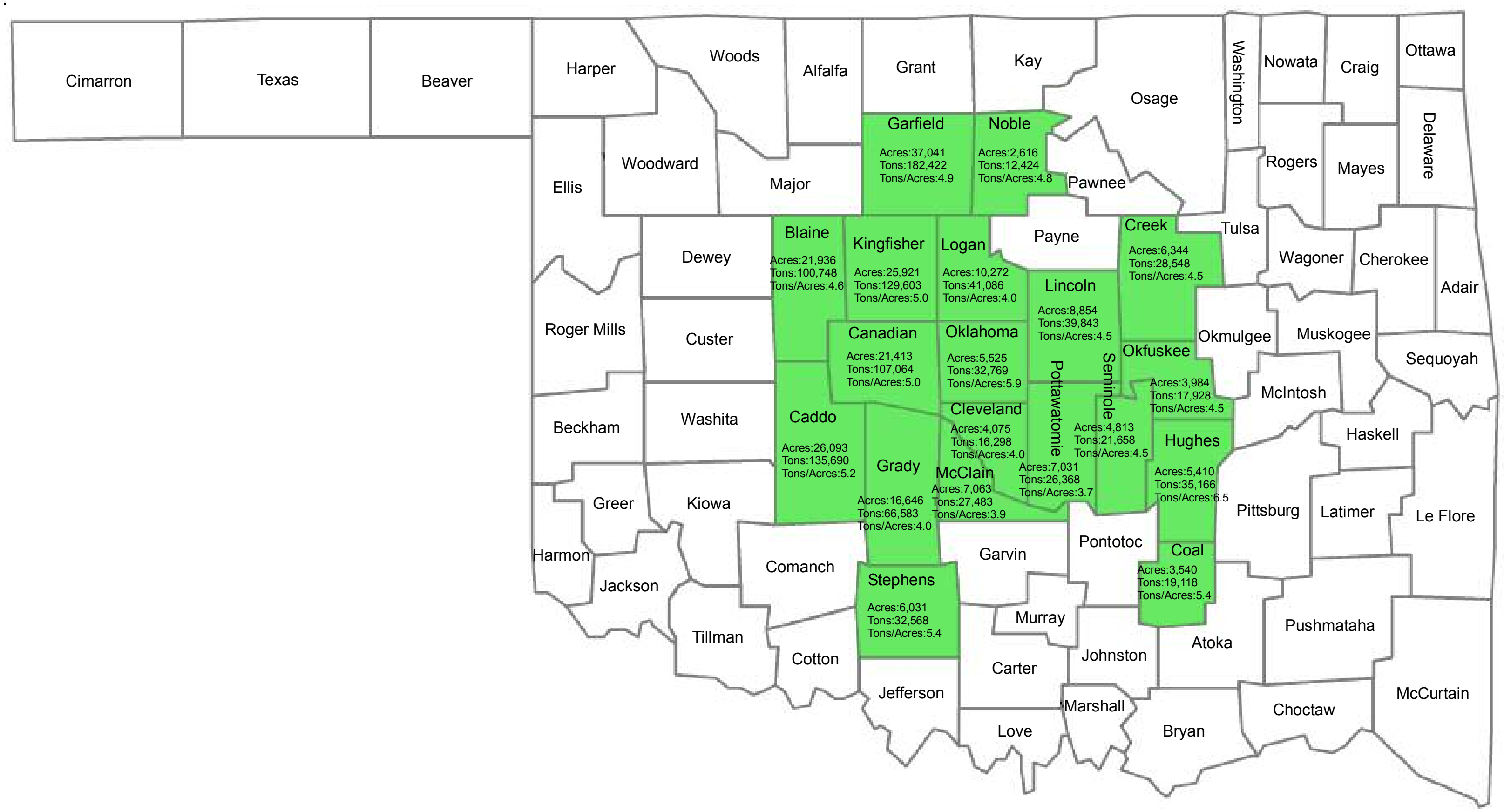

Figure 49. Map of Oklahoma Showing the Number of Acres, Harvested Tons, and Yield per Acre of Counties Harvesting Switchgrass for 3,000 Dry Tons per Day Biorefinery Located in Canadian County

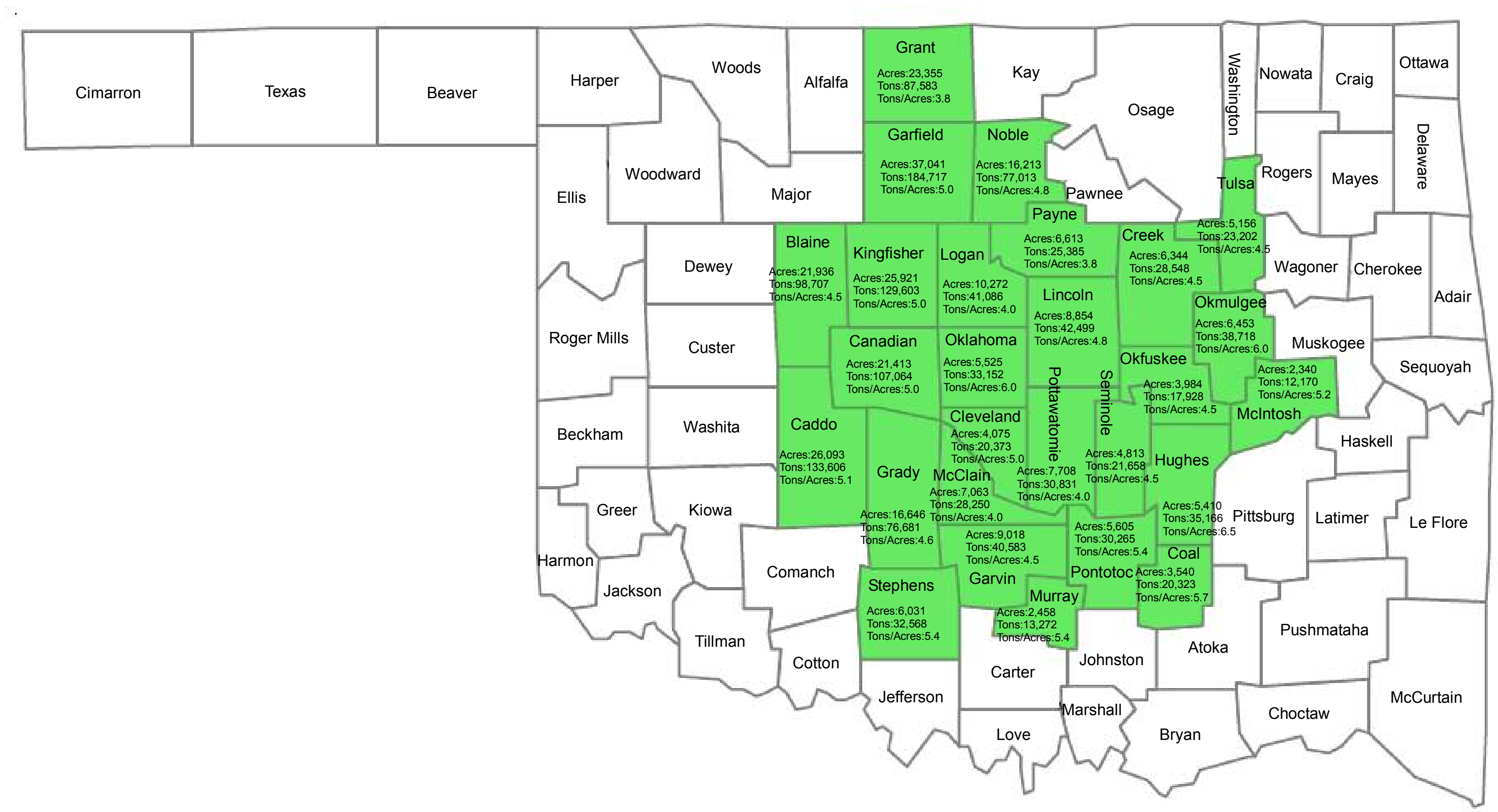

Figure 50. Map of Oklahoma Showing the Number of Acres, Harvested Tons, and Yield per Acre of Counties Harvesting Switchgrass for 4,000 Dry Tons per Day Biorefinery Located in Canadian County

CHAPTER VI

SUMMARY AND CONCLUSIONS

The Energy Policy Act of 2005 includes a provision that by 2013, a minimum of 250 million gallons per year of ethanol be produced from LCB source such as crop residues and switchgrass. In the absence of government subsidies or other non-market incentives, to achieve this goal an economically competitive LCB ethanol biorefinery system would have to be developed. The economic success of an LCB ethanol biorefinery will depend upon a sustainable supply of LCB feedstock and on achieving total production costs competitive with that of grain-based and sugarcane-based ethanol.

Switchgrass was selected by the Department of Energy's Oak Ridge National Laboratory as an LCB feedstock after screening a variety of potential alternatives. Switchgrass is a warm season native perennial grass that can grow throughout the Great Plains. Ultimately, the success of an LCB-based biorefinery will depend in part upon the cost to produce, harvest, store, and transport a substantial quantity feedstock. The cost of delivered feedstock will be a key component.

Previous studies have found that the cost of harvesting feedstock is a major cost component. Harvest cost will depend on the number of required harvest machines. The number of required harvest machines depends on the number of field workdays during the harvest window. Incorrect estimates of the number of workdays would result in incorrect feedstock harvest cost estimates and an incorrect estimate of the investment required in harvest machinery. However, it is difficult to precisely determine the available number of harvest days because harvest operations are heavily weather dependent.

To address these issues, a model was designed to determine the number of field workdays considering both switchgrass mowing and switchgrass baling operations and to determine the effect of the number of workdays on the cost to deliver a flow of feedstock to a biorefinery. Specific objectives were to: (i) develop a general soil moisture balance model; (ii) develop a drying model for switchgrass on the ground after cutting; (iii) determine the probability distribution of the number of suitable field workdays per month; (iv) determine how the number of field workdays for the mowing operation and the baling operation can be incorporated into Mapemba's extension of Tembo's model; (v) determine the optimal number of harvest machines for a biorefinery located in Oklahoma and the cost to procure, harvest, store, and transport a flow of switchgrass feedstock to a 1,000, 2,000, 3,000, and 4,000 dry tons per day biorefinery, and how restrictions on the number of workdays influence cost.

To achieve the first objective, a soil moisture balance model developed by Allen et al. (1998) was adapted and used to determine the ability to use harvest machines such as mowers and balers in the field without damaging the soil. To complete the second objective, a cut grasses moisture content model developed by Rotz and Chen (1985) was adapted to determine when the moisture content of mowed switchgrass would be below the threshold level of 15 percent, which is considered a safe level for baling.

Daily and hourly meteorological data from the Oklahoma Mesonet system were used for both the soil moisture balance model and cut grasses moisture content model.

The Mesonet system records and archives data at each site, every five minutes. The 4,533 days for which Mesonet data were available provided more than 1.3 million observations for each variable for each of nine locations. Microsoft Excel and SAS software were used to manage the data. In both models days suitable for use of harvest machines were defined as workdays. The monthly number of mowing days and baling days for switchgrass in each of nine regions was independently estimated.

To achieve the third objective, probability distributions were produced for both mowing and baling operations using an empirical CDF. The number of workdays for mowing and baling varies across months and regions. At the 95 percent probability level, October is the month with the least amount of time for baling switchgrass (average nine days). The southeast region, which on average receives the most precipitation, has the least number of available workdays (174 mowing days and 115 baling days for a year). The models confirm that precipitation is a dominant factor for determining the number of field workdays.

To address the fourth objective, a mixed integer mathematical programming model was used. The mixed integer mathematical programming algorithm available in the CPLEX solver in the generalized algebraic modeling system (GAMS) software was used to solve the model. This model extends the model developed by Mapemba (2005) in the following respects: (i) it incorporates the number of harvest days available in each month for each of the nine regions of the state based upon various weather variables and historical weather data from the Oklahoma Mesonet system; (ii) it differentiates between the number of harvest days by type of harvesting operation: the number of mowing days and the number of raking-baling-stacking days; (iii) it also differentiates between a mowing harvest unit and a raking-baling-stacking harvest unit; and (iv) it assumes that harvest capacity for mowing and raking-baling-stacking varies across months with the quantity of daylight. The model also differs from Mapemba's in that it considers switchgrass grown on cropland as the only feedstock.

Mowing unit integer activities and raking-baling-stacking unit integer activities were incorporated into the model (See equation 4.24 through 4.28). For the Base Model, the average annual cost of a mowing unit integer activity and a raking-baling-stacking unit integer activity was estimated to be $58,424 and $470,236, respectively. Monthly capacities of the mowing unit integer activity and the raking-baling-stacking unit integer activity were also estimated (see Table 11 in Chapter 4).

To determine how harvest days influence cost (objective five), four different situations differentiated by the numbers of workdays were modeled: Base WD (the number of workdays from the results estimated in this study), Reinschmiedt WD (the number of workdays from Reinschmiedt's study, these estimates were used by Mapemba.), Most WD (30 days available in each month), and Least WD (three days available in each month). It was determined that the estimated cost to deliver a flow of switchgrass feedstock to a 2,000 dry tons per day biorefinery was $40 per ton for the Most WD and $141 per ton for the Least WD models. Estimated harvest cost was $8 and $109 per ton for the Most WD and the Least WD models, respectively. Increased workdays requires fewer harvest units and results in lower harvest cost.

In the Base WD model, the estimated cost to deliver feedstock was $49.70 per ton compared to $46.40 per ton for the Reinschmiedt WD model. Harvest costs were estimated to be $17.00 and $12.60 per ton for the two models, respectively. The optimal number of harvest units for the Base WD model was 48 for mowing and 20 for raking-baling-stacking, which requires an average investment in harvest machines of $11.2 million. If the Reinschmiedt estimate of workdays is used, the model estimates that only 41 mowing and 14 raking-baling-stacking harvest units would be required which would have underestimated the average investment of harvest machines by about $3 million. By this measure, since Mapemba (2005) used the Reinschmiedt estimates of workdays, he underestimated harvest costs because of the overestimate of the number of harvest days.

It is not possible to validate the feedstock delivery cost estimates produced in this study. Currently no switchgrass is being produced commercially as a dedicated energy crop in Oklahoma. However, it is possible to compare results across studies. The estimates obtained in this study are consistent with those of other studies. For example, Tiffany et al. (2006) estimated the cost to produce native prairie grass including switchgrass in the northern Great Plains of about $36 per ton (including land rental payment, harvest cost, establishment cost, and maintenance cost). Their finding is similar to those of this study ($37 per ton). Tiffany et al. (2006) estimated harvest costs to be about $18.50 per ton. This can be compared with the estimate of $17.00 per ton found in this study. According to the report by Leistritz et al. (2006), delivery cost of switchgrass feedstock in Nebraska, South Dakota, and North Dakota was estimated to be about $50 per ton (including transportation cost), which is similar to this study's finding of $49.70 per ton.

This study also determined the cost to deliver a flow of switchgrass feedstock to a biorefinery with four capacity levels (1,000, 2,000, 3,000, and 4,000 dry tons per day) under the workdays assumption of the Base WD. It was determined that the estimated delivery cost increased from about $48 to $53 per ton as biorefinery feedstock requirements increased from 1,000 to 4,000 dry tons per day. This is because transportation cost increases as the biorefinery size increases.

For a biorefinery with daily capacity of 1,000 dry tons, switchgrass would be annually harvested from about 65,000 acres across 11 counties. A 2,000 dry tons per day biorefinery would require the harvest of about 129,000 acres across 21 counties, a 3,000 dry tons per day require about 196,000 acres across 31 counties, and a 4,000 dry tons per day require about 270,000 acres across 41 counties. For these models the optimal biorefinery location was estimated to be Okmulgee County.

For the biorefinery located in Canadian County, the 1,000 tons per day facility would require the annual harvest of about 74,000 acres across 5 counties, the 2,000 tons per day require about 148,000 acres across 11 counties, the 3,000 tons per day require about 225,000 acres across 19 counties, and the 4,000 tons per day require about 300,000 acres across 27 counties.

For a successful biorefinery system, production, harvest, storage, and transportation of feedstock may be coordinated. Harvest cost is a key component of the total cost to deliver feedstock. Harvest cost depends upon the number of harvest units, which have capacity limits. System harvest capacity is restricted by the available number of workdays which depends upon weather conditions. This study is the first to address the influence of weather on harvest capacity and required investment in harvest machines.

This study has shown that the cost to deliver a flow of switchgrass feedstock to a biorefinery is sensitive to the number of workdays for harvesting. This study has provided a framework for estimating field workdays and for differentiating between days suitable for mowing and days suitable for baling.

There are several limitations of this study. First, only 12 years and five months of Mesonet data were available to estimate the number of workdays available in each month. Hence, frequencies to estimate a probability distribution of the number of workdays per month were 12 or 13 observations. Clearly, when dealing with weather, especially weather in the Great Plains of the U.S., observations from a much longer time period would be preferred to obtain a more reliable number of monthly harvest days.

Further research could be conducted to attempt to mitigate this limitation. Based upon the number of workdays estimated in this study, a statistical model could be designed to predict workdays as a function of a limited number of major weather variables such as rainfall and temperature. About 100 Oklahoma weather stations have recorded both rainfall and temperature for a long period, more than 50 years (Coop Data in Oklahoma Climate Data, http://climate.ocs.ou.edu). Namely, the estimated coefficients could be obtained from the Poisson regression model with the number of mowing days or baling days in a certain region for a month estimated in this study as a dependent variable and available weather data as independent variables. The available weather data are cumulative precipitation for a month, monthly average temperature, maximum and minimum temperature for a month, and the number of rainfall for a month. As these weather data obtained from weather stations recording both rainfall and temperature for 50 years plug in this prediction model, at least 50 observations per month per region could be obtained. Potentially the estimated workday CDFs could be augmented with a number of additional observations based upon predicted values from estimated a Poisson regression model.

A second limitation is that while the component equations used in the models to estimate the number of workdays have been validated by other researchers, actual recorded data for the number of suitable harvest days were not available to validate the results obtained for the nine regions.

Third, since there is no commercial production of switchgrass in Oklahoma, some of the data used in the model were from hypothetical situations. For instance, the proportion of cropland acres for planting switchgrass was limited to 10 percent per county. If more land could be leased per county, overall transportation costs would be lower. County yields of switchgrass were based upon results from experiment station trials rather than from farm level results. Similarly, switchgrass production cost estimates were based upon results of experiment station trials rather than from farm level data. The degree of accuracy of the results depends upon the extent to which the assumptions regarding production costs and yields concur with actual costs and yields.

Due to the absence of a commercial market for switchgrass, the model was setup to mimic a vertically integrated, rather than atomistic, structure. Farmers are not likely to plant switchgrass until a reliable market is established. Similarly, entrepreneurs are not likely to invest in a biorefinery until they can be assured of a reliable level of feedstock. Given these circumstances, the model was designed to simultaneously determine optimal land requirements, biorefinery location, feedstock production, harvest, storage, and transportation. To insure a sufficient quantity of feedstock, a processing firm could enter into long-term contracts with land owners or farmers. However, if only one biorefinery exists in a region, it would potentially have monopsony power. Established switchgrass has few alternative uses. After the perennial grass is established, farmers (landowners) would be at a bargaining disadvantage. Additional research would be required to identify strategies that could be employed to reduce the likelihood of entrepreneurs exercising monopsony power. Additional research could also be conducted to determine the consequences of a feedstock supply system dependent upon spot markets resembling the U.S. grain and oilseed market structure.

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APPENDICES

APPENDIX A -- Reference Evapotranspiration and Crop Coefficient

Reference Evapotranspiration

There are several methods for estimating reference evapotranspiration, $ET_{o.}$ Among these methods, Allen et al. (1998) recommend the Penman-Moneith because it needs minimal calibrations for adjusting to local weather conditions. Thus, this study employs the FAO Penman-Monteith equation to estimate ET_o. The FAO Penman-Monteith (FAO-PM) equation is (Allen et al. 1998; Sutherland, Carlson, and Kizer 2005)

$$(A.1) \qquad ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{C_n}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)}$$

where R_n is a net radiation at the crop surface (MJ $m^{-2}d^{-1}$), G is a soil heat flux density at the soil surface (MJ $m^{-2}d^{-1}$), T is a mean daily air temperature at two meter height (°C), u_2 is a mean daily wind speed at two meter height (m s^{-1}), e_s is a saturation vapor pressure (kPa), e_a is a mean actual vapor pressure (kPa), Δ is a slope vapor pressure curve (kPa $°C^{-1}$), γ is a psychrometric constant (kPa $°C^{-1}$), C_n is a numeration constant that changes with reference type and calculation time step, and C_d is a denominator constant that changes with reference type and calculation time step.

The values for C_n consider time step and aerodynamic roughness of the surface. The constant denominator C_d considers the time step, bulk surface resistance, and aerodynamic roughness of the surface. Table A-1 provides values for C_n and C_d.

Table A-1. Values for C_n and C_d

Calculation time step	Short grass ET$_o$[a]		Tall grass ET$_o$[b]	
	C_n	C_d	C_n	C_d
Daily	900	0.34	1600	0.38
Hourly during daytime	37	0.24	66	0.25
Hourly during night time	37	0.96	66	1.7

[a] The height of short grass is 0.12 m (4¾ inches)
[b] The height of tall grass is 0.50 m (19¾ inches)
Source: Sutherland, Carlson, and Kizer (2005)

Net radiation R_n, was computed from:

(A.2)
$$R_n = 0.77R_s - \sigma\left(\frac{T_{\max,K}^4 + T_{\min}^4}{2}\right)\left[a_c\left(\frac{R_s}{R_{so}}\right) + b_c\right]\left(a_1 + b_1\sqrt{e_a}\right)$$

where R_s is measured incoming solar radiation in MJ m^{-2}d^{-1}, R_{so} is computed clear sky solar radiation in MJ m^{-2}d^{-1}, e_a is the mean actual vapor pressure in kPa, σ is the Stefan-Boltzmann constant equal to 4.90×10^{-9} MJ m^{-2} K^{-1} d^{-1}, $T_{\max,K}$ is the daily maximum air temperature in K (Kelvin, K= °C + 273.16), $T_{\min,K}$ is the daily minimum air temperature in K, and a_c, b_c, a_1, and b_1 are constants equal to 1.35, -0.35, 0.34, and -0.14, respectively.

Clear sky solar radiation was computed from:

(A.3)
$$R_{so} = (a_s + b_s z)R_a$$

where z is station elevation in m, R_a is the computed extraterrestrial radiation in MJ m^{-2}d^{-1}, and a_s and b_s are constants.

Oklahoma Mesonet provides values for a_s and b_s (Sutherland, Carlson, and Kizer 2005).

Table A-2. Values of a_s and b_s

Julian Day	a_s	b_s
1-104, 288-366	0.720	4.88×10^{-5}
105-134, 257-287	0.705	5.07×10^{-5}
135-256	0.685	5.28×10^{-5}

Source: Sutherland, Carlson, and Kizer (2005)

Extraterrestrial radiation is obtained from:

(A.4) $$R_a = 37.6 d_r (\omega_s \sin\phi \sin\delta + \cos\phi \cos\delta \sin\omega_s)$$

where d_r is the inverse relative distance between the earth and sun, ω_s is the sunset hour angle in rad, ϕ is the latitude in rad, and δ is the solar declination in rad.

The latitude, ϕ, expressed in radians is positive for the northern hemisphere and negative for the southern hemisphere. The conversion from decimal degree to radians is given by:

(A.5) $$\text{Radians} = \frac{\pi}{180}(\text{decimal degree})$$

The inverse relative distance between the earth and sun is given by:

(A.6) $$d_r = 1 + 0.003\cos(0.0172J)$$

where J is the day number in the year (Julian day).

Sunset hour angle is obtained from:

(A.7) $$\omega_s = \arccos(-\tan\phi \tan\delta)$$

Solar declination is computed by:

(A.8) $$\delta = 0.409 \sin(0.0172J - 1.39)$$

Soil heat flux, G is computed by:

(A.9) $$G = c_s \frac{T_i + T_{i-1}}{\Delta t} \Delta z$$

where, c_s is soil heat capacity in $\text{MJ m}^{-2}\text{d}^{-1}$, T_i is air temperature at time i in °C, T_{i-1} is air temperature at time i-1 in °C, Δt is length of time interval in day, and Δz is effective soil depth in m.

In this study, soil heat flux, G, was assumed equal to zero because soil heat flux beneath the grass reference surface is relatively small (Allen et al. 1998). The psychrometer constant, γ, is computed by:

(A.10) $$\gamma = 0.00163 \left(\frac{P}{\lambda} \right)$$

where P is atmospheric pressure in kPa and λ is assumed to be a constant value of 2.45 MJ kg^{-1}.

Atmospheric pressure was estimated from elevation in m above sea level, z by:

(A.11) $$P = 101.3 \left(\frac{293 - 0.0065z}{293} \right)^{5.26}$$

Slope of the saturation vapor pressure curve is computed by:

(A.12) $$\Delta = \frac{4908 \left[0.618 \exp \left(\frac{17.27T}{T + 237.3} \right) \right]}{(T + 237.3)^2}$$

where, T is the mean air temperature for the day in °C.

Saturation vapor pressure and actual mean vapor pressure were computed from:

(A.13) $$e_s = \frac{e^o(T_{\max}) + e^o(T_{\min})}{2}$$

(A.14) $$e_a = e^0(T_{dew})$$

where $T_{\max}$, $T_{\min}$, and T_{dew} are daily maximum temperature (°C), minimum temperature (°C), and dew point temperature (°C), respectively.

Vapor pressure $e^0(T)$ is compute by:

(A.15) $$e^o(T) = 0.6108 \exp\left(\frac{17.27T}{T + 237.3}\right)$$

When solar radiation data, relative humidity data and wind speed data are missing, an alternative reference ET_o can be estimated using the Hargreaves ET_o equation where:

(A.16) $$ET_o = 0.0023\left(\frac{T_{\max} + T_{\min}}{2} + 17.8\right)\left(T_{\max} - T_{\min}\right)^{0.5} R_a$$

Crop Coefficient

The FAO-PM model is applicable only when the entire evaporating surface area is covered with water to saturation and the vegetation offers no resistance water to vapor transfer. Therefore, it depends only on energy supplied from the climate and is independent of the surface characteristics. It represents the maximum possibilities for evaporation for a given climatic condition. However, actual evapotranspiration is highly variable since it depends on climatic conditions (especially radiation balance and wind), on surface water availability, i.e. resistances to the transfer of water from vegetation to the atmosphere (affected by leaf area, the fraction of ground covered by vegetation, leaf age and condition, and soil surface wetness), and on the nature of the plant above ground (Guyot 1998; Allen 2000).

Actual evapotranspiration (ET) realized from the specific crop is given by:

(A.17)
$$ET = K_c ET_o$$

where K_c is a crop coefficient.

Allen et al. (1998) introduced the concept of a dual crop coefficient to allow computation of more precise estimates of daily evapotranspiration. For the dual crop coefficient, soil evaporation and the effect of crop transpiration are separated. In addition, Allen et al. (1998) considered the effect of water stress on crop transpiration. When the soil is wet, plants easily uptake water via their roots. However, in dry soil, it may be difficult for plants to absorb water and the plant is said to be water stressed.

Crop coefficient can be expressed by:

(A.18)
$$K_c = K_s K_{cb} + K_e$$

where K_s is the stress reduction coefficient (0~1.0), K_{cb} is the basal crop coefficient (0~1.4), and K_e is the soil water evaporation coefficient (0~1.4).

Basal Crop Coefficient

Basal crop coefficient, K_{cb} (primary crop transpiration), is defined as the ratio of the acutal evapotranspiration over the reference evapotranspiration (ET / ET_o) when the soil is dry but transpiration is not limited by water supply (Burman and Pochop 1994; Allen et al. 1998; Hunsaker, Pinter, and Kimball 2005; Kato and Kamichika 2006). Allen et al. (1998, hereafter FAO-56) provided basal crop coefficient values for four growth stage periods: the initial, the development, the midseason, and the late season. Parts of table 17 from the FAO-56 study are included in Table A-3.

Table A-2. The Basal Crop Coefficient from FAO-56, Table 17

Crop	$K_{cb\ \mathrm{ini}}$	$K_{cb\ \mathrm{mid}}$	$K_{cb\ \mathrm{end}}$
Alfalfa Hay – individual cutting periods	0.34	1.15	1.10
– for seed	0.30	0.45	0.45
Bermuda Hay – averaged cutting effects	0.50	0.95	0.80
– spring crop for seed	0.15	0.85	0.60
Clover hay, Berseem – individual cutting periods	0.30	1.10	1.05
Rye Grass hay – averaged cutting effects	0.85	1.00	0.95
Sudan Grass hay (annual) – individual cutting periods	0.30	1.10	1.05
Grazing Pasture – Rotated Grazing	0.30	0.80-1.00	0.80
– Extensive Grzaing	0.30	0.70	0.70
Turf grass – cool season	0.85	0.90	0.90
– warm season	0.75	0.80	0.80

Source: Allen et al. (1998)

When the mean daily minimum relative humidity ($\mathrm{RH}_{\min}$) differs from 45% or wind speed at two meter height is larger or smaller than 2m s^{-1} during the midseason, K_{cb} in the midseason, $K_{cb\ \mathrm{mid}}$ should be adjusted as shown in equation (A.19) (Allen et al. 1998).

(A.19) $$K_{adj.cb\ \mathrm{mid}} = K_{cb\ \mathrm{mid}} + \left[0.04(u_2 - 2) - 0.004(\mathrm{RH}_{\min} - 45)\right]\left(\frac{h}{3}\right)^{0.3}$$

where $K_{cb\ \mathrm{mid}}$ is the value of basal crop coefficient during the midseason, u_2 is the mean value for daily wind speed at two meter height during the midseason in m s^{-1}, $\mathrm{RH}_{\min}$ is the mean daily minimum relative humidity in percent, and h is the mean plant height during the midseason in m. Likewise, K_{cb} at the end of the growing season, $K_{cb\ \mathrm{end}}$, can be adjusted as shown in equation (A.20).

(A.20) $$K_{adj.cb\ \mathrm{end}} = K_{cb\ \mathrm{end}} + \left[0.04(u_2 - 2) - 0.004(\mathrm{RH}_{\min} - 45)\right]\left(\frac{h}{3}\right)^{0.3}$$

Evaporation from Soil

Evaporation from soil beneath a canopy or in between plants can be predicted by estimating the amount of energy available at the soil surface. This energy is what remains following consumption of energy by transpiration. Transpiration is approximated as $K_{cb}ET_o$. When the soil is wet, evaporation is presumed to occur at some maximum rate and the sum $K_c = K_{cb} + K_e$ is set at some maximum value $K_{c\,\max}$. When the top soil dries, a reduction in evaporation occurs:

(A.21) $$K_e = K_r(K_{c\,\max} - K_{cb}) \le f_{ew}K_{c\,\max}$$

where K_e is the soil evaporation coefficient, K_r is a dimensionless evaporation reduction coefficient dependent on the cumulative depth of water depleted (evaporated) from the topsoil, f_{ew} is the fraction of the soil that is both exposed and wetted, i.e., the fraction of soil surface from which most evaporation occurs, and $K_{c\,\max}$ is the maximum value of K_c flowing rain or irrigation.

Evaporation is restricted by the energy available at the exposed soil fraction, i.e. K_e cannot exceed $f_{ew}K_{c\,\max}$ (Allen 2000). $K_{c\,\max}$ is computed as shown in equation A.22.

(A.22) $$K_{c\,\max} = \max\left(\left\{1.2 + \left[0.04(u_2 - 2) - 0.004(\mathrm{RH}_{\min} - 45)\right]\left(\frac{h}{3}\right)^{0.3}\right\}, \left\{K_{cb} + 0.05\right\}\right)$$

where h is the mean maximum plant height during the period of calculation (initial, development, mid-season, or late-season) in m.

Soil evaporation from the exposed soil is presumed to take place in two stages: an energy limiting stage (stage 1) and a falling rate stage (stage 2). During stage 1, the soil surface remains wet and it is assumed that evaporation will occur at the maximum rate limited only by energy availability at the soil surface and therefore, $K_r = 1$. Stage 1 holds until the cumulative depth of evaporation, D_e is such that the hydraulic properties of the upper soil become limiting and water cannot be transported to the soil surface at a rate that can supply the potential demand. At the end of stage 1 drying, D_e is equal to readily evaporable water (REW). If the total evaporable water (TEW) is depleted, then K_r becomes zero.

In stage 2, evaporation decreases in proportion to the amount of water remaining in the surface soil layer:

(A.23) $$K_r = \frac{TEW - D_{e,i-1}}{TEW - REW} \quad \text{for } TEW > D_{e,i-1}$$

where $D_{e,i-1}$ is cumulative depth of depletion or evaporation from the soil surface layer at the end of day i-1 (the previous day) in mm, TEW is total evaporable water in mm, and REW is readily evaporable water in mm.

TEW is the maximum depth of water that can be evaporated from the soil when the topsoil has been initially completely wetted. TEW is computed by:

(A.24) $$TEW = 1000(\theta_{FC} - 0.5\theta_{WP})Z_e$$

where θ_{FC} is soil water content at field capacity in $\mathrm{m^3\ m^{-3}}$, θ_{WP} is soil water content at wilting point in $\mathrm{m^3\ m^{-3}}$, and Z_e is depth of the surface soil layer that is subject to drying by way of evaporation in m (Allen 2000).

θ_{FC}, θ_{WP}, TEW and REW vary with soil type. Typical values for θ_{FC}, θ_{WP}, TEW and REW are given below table.

Table A-3. Typical Soil Water Characteristics for Different Soil Types

Soil type	Soil water characteristics			Evaporation parameters	
	θ_{FC}	θ_{WP}	(θ_{FC} - θ_{WP})	REW	TEW (Z_e =0.1m)
	(m^3 m^{-3})	(m^3 m^{-3})	(m^3 m^{-3})	(mm)	(mm)
Sand	0.07-0.17	0.02-0.07	0.05-0.11	2-7	6-12
Loamy sand	0.11-0.19	0.03-0.10	0.06-0.12	4-8	9-14
Sandy loamy	0.18-0.28	0.06-0.16	0.11-0.15	6-10	15-20
Loam	0.20-0.30	0.07-0.17	0.13-0.18	8-10	16-22
Silt loam	0.22-0.36	0.09-0.21	0.13-0.19	8-11	18-25
Silt	0.28-0.36	0.12-0.22	0.16-0.20	8-11	22-26
Silt clay loam	0.30-0.37	0.17-0.24	0.13-0.18	8-11	22-27
Silty clay	0.30-0.42	0.17-0.29	0.13-0.19	8-12	22-28
Clay	0.32-0.40	0.20-0.24	0.12-0.20	8-12	22-29

Source: Allen et al. (1998)

Both location and the fraction of the soil surface exposed to sunlight change to some degree with the time of day depending on row orientation. The procedure presented here predicts a general averaged fraction of the soil surface from which the majority of evaporation occurs. Diffusive evaporation from the soil beneath the crop canopy is assumed to be largely included in the basal K_{cb} coefficient.

Where the complete soil surface is wetted, either by precipitation or irrigation, the fraction of the soil surface from which most evaporation occurs, f_{ew}, is defined as $(1-f_c)$, where f_c is the average fraction of soil surface covered by vegetation and $(1-f_c)$ is the approximate fraction of soil surface that is exposed. f_{ew} is computed by:

(A.25) $$f_{ew} = \min(1-f_c, f_w)$$

where $1-f_c$ is average exposed soil fraction not covered by vegetation (0.01~1.0), and f_w is average fraction of soil surface wetted by precipitation or irrigation (0.01~1.0).

When f_c is not measured, f_c is estimated as:

(A.26) $$f_c = \left(\frac{K_{cb} - K_{c\ \min}}{K_{c\ \max} - K_{c\ \min}} \right)^{(1+0.5h)}$$

where f_c is the effective fraction of soil surface covered by vegetation (0~0.99), $K_{c\ \min}$ is the minimum K_c for dry bare soil with no ground cover ($\approx$0.15~0.20), which is approximately the same value of $K_{cb\ \text{ini}}$, and h is the mean plant height in m (Allen et al. 1998).

Water Stress

The water stress coefficient, K_s is given by:

(A.27) $$K_s = \frac{TAW - D_r}{TAW - RAW} \quad \text{for } D_r > RAW$$

where K_s is a dimensionless transpiration reduction factor dependent on available soil water (0~1.0), D_r is depletion in soil profile in mm, TAW is total available soil water in the soil profile in mm, and RAW is the readily available soil water in the soil profile in mm. When $D_r \le RAW$, K_s=1.

Total available water in the soil profile is:

(A.28) $$TAW = 1000(\theta_{FC} - \theta_{WP})Z_r$$

where Z_r is soil profile depth in m.

Readily available soil water is estimated as:

(A.29) $$RAW = pTAW$$

where p is the fraction of TAW that a crop can extract water without suffering water stress.

APPENDIX B -- Summary of Indices, Parameters, and Variables

Table B-1. Model Indices and Their Descriptions

Index	Descriptions and member elements
Main Sets	
M	Month: *m* = {Mar, Apr, May, Jun, Jul, Aug, Sep, Oct, Nov, Dec, Jan, Feb}
J	Set of counties located prospective plant: *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 77 counties in Oklahoma}
F	Set of level of nitrogen application (lbs/acre): *f* = {80}
Ft	Set of facilities: *ft* = {Processing facility, Storage facility}
Subsets	
b(g)	Set of process byproducts or externalities: *b* = { CO_2, N_2, Ash}
e(g)	Set of process main product: *e* = {ethanol}

Table B-2. Descriptions of the Model Parameters

Parameter	Description
ρ_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.
α	Cost of producing a ton of switchgrass
γ	Cost of storing a ton of switchgrass in the field
τ_{ij}	Round-trip cost of transporting a ton of biomass from source country *i* to plant location *j*
ω	Annual cost of a harvest unit for mowing
$\overline{\omega}$	Annual cost of a harvest unit for raking-baling-stacking
θ_i	Proportion of switchgrass stored in county *i* that is usable a month later
ϕ_j	Proportion of switchgrass stored at plant *j* that is usable a month later
λ_g	Quantity of output *g* produced from a ton of switchgrass at the plant
λ_e	Quantity of ethanol (*e*) produced from a ton of switchgrass at the plant
$LAND_i$	Total acres of land not enrolled in CRP producing switchgrass in county *i* (acres)
BP_l	Proportion of cropland in county *i* with switchgrass available for harvesting for biorefinery use
YAD_m	Yield adjustment factor for switchgrass if harvested in month *m*
$BYLD_{kf}$	Yield (tons/acres/year) of switchgrass if under fertility regime *f* at county *i*
$TAFC_{sft}$	Amortized fixed cost of constructing and operating facility *ft* of plant size *s*
$CAPHUM_{im}$	Capacity of harvest unit for mowing in month *m* at county *i*
$CAPHUB_{im}$	Capacity of harvest unit for raking-baling-stacking in month *m* at county *i*
$CAPP_s$	Processing facility capacity associated with plant size *s* (gallons of ethanol per month)
$CAPS_s$	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*

Table B-3. Descriptions of Variables

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_{ifm}	Acres of switchgrass harvested at source *i* in month *m*, where switchgrass is under fertility regime *f*
xsp_{im}	Tons of switchgrass harvested in month *m* and stored in county *i*
xt_{ijsm}	Tons of switchgrass transported in month *m* at source *i* to a plant size *s* at location *j*
x_{ifm}	Tons of switchgrass harvested in month *m* at source *i*, where switchgrass is under fertility regime *f*
xs_{im}	Tons of switchgrass stored at source county *i* in month *m*
xsn_{im}	Tons of switchgrass removed from storage at source *i* in month *m*
$xhum_{im}$	Proportion of a harvest unit for mowing used in county *i* in month *m*
$xhub_{im}$	Proportion of a harvest unit for raking-baling-stacking used in county *i* in month *m*
HUM	Integer variable representing the total number of mowing harvest units used
HUB	Integer variable representing the total number of raking-baling-stacking harvest units used
xs_{jm}	Tons of switchgrass stored at plant location *j* in month *m*
xp_{jsm}	Tons of switchgrass processed by a plant of size *s* at plant location *j* in month *m*
β_{js}	A binary variable associated with plant size *s* at location *j*

APPENDIX C -- Harvest Machines, Costs, and Capacities

Table C-1. Harvest Machine and Machine Characteristics to Estimate Harvest Cost and Capacities

Unit	Price	Hours Life
95 hp Tractor	$44,300	10,000
155 hp Tractor	$63,200	10,000
Mower, Rotary (10-feet)	$20,000	2,500
Rake, Twin Wheel (10 feet)	$6,000	2,500
Baler, Large Square (4 feet × 4 feet × 8 feet)	$67,000	3,000
Bale Transporter Stacker	$115,000	10,000

Note: A mower is pulled by a 95 horse power tractor.
A rake is pulled by a 95 horse power tractor.
A baler is pulled by 150 horse power tractor.
Self-propelled bale transporter collects as many as eight large rectangular solid bales, transports them and stacks them in the filed or at a location within ten miles.
Source: Thorsell (2004)

Table C-2. The Annual Operating and Maintenance Cost of a Mowing Harvest Unit per Acre for the Base WD, Reinschmiedt WD, and Most WD Models

	Yield per Acre (Tons)						
	1	2	3	4	5	6	Average
Annual Acres	16,156	9,140	6,093	4,570	3,656	3,047	
Mower and Tractor							
Fixed Costs per Acre ($)	0.73	1.15	1.74	2.31	2.88	3.48	
Variable Costs per Acre ($)	1.69	2.37	3.59	4.73	5.92	7.17	
Mowing Harvest Unit							
Labor per Acre ($)	1.55	2.74	4.10	5.47	6.84	8.21	
Fixed Costs per Acre ($)	0.73	1.15	1.74	2.31	2.88	3.48	
Machine Variable Costs per Acre ($)	1.69	2.37	3.59	4.73	5.92	7.17	
Total Per Acre Costs ($)	3.97	6.26	9.43	12.51	15.64	18.86	
Total Annual Cost ($/HU)	64,098	57,173	57,477	57,173	57,173	57,447	58,424

Note: A mowing harvest unit includes one laborer, one mower, and one tractor.

Table C-3. The Annual Operating and Maintenance Cost of a Raking-Baling-Stacking Harvest Unit per Acre for the Base WD, Reinschmiedt WD, and Most WD Models

	Yield per Acre (Tons)						
	1	2	3	4	5	6	Average
Annual Acres	48,469	27,420	18,280	13,710	10,968	9,140	
Transporter-Stacker							
Fixed Costs per Acre ($)	0.31	0.55	0.82	1.09	1.37	1.64	
Variable Costs per Acre ($)	0.48	0.84	1.27	1.7	2.11	2.54	
Rakes, Balers, Tractors							
Fixed Costs per Acre ($)	1.98	3.42	5.18	6.83	8.49	10.29	
Variable Costs per Acre ($)	3.94	5.99	9.17	11.99	13.05	16.01	
Raking-Baling-Stacking Harvest Unit							
Labor per Acre ($)	3.61	6.38	9.58	12.77	15.95	19.14	
Fixed Costs per Acre ($)	2.29	3.97	6.00	7.92	9.86	11.93	
Machine Variable Costs per Acre ($)	4.42	6.83	10.44	13.69	15.16	18.55	
Total Per Acre Costs ($)	10.32	17.18	26.02	34.38	40.97	49.62	
Total Annual Cost($/HU)	500,327	471,206	475,593	471,344	449,380	453,567	470,236

Note: A raking-baling-stacking harvest unit includes seven laborers, three rakes, three balers, six tractors, and a field Stacker. Raking costs were added to yields of 4.5 tons per acre and greater. The costs were based on operating the rakes 20% of the time.

This table includes yields of one, two, and three tons per acre even though yields of switchgrass were assumed to be five through six and half tons per acre. Harvestable yield is also a function of YAD. For instance, for a YAD of 0.75, the yield of five tons per acre would change to 3.75 tons per acre. Furthermore, the throughput capacity of the machines (tons per hour) is assumed to be approximately the same across fields with different yields. Speeds are adjusted so that tons harvested per hour remain relatively constant independent of yield per acre.

Table C-4. The Annual Operating Maintenance Cost of a Mowing Harvest Unit per Acre for the Least WD Model

	Yield per Acre (Tons)						
	1	2	3	4	5	6	Average
Annual Acres	16,156	9,140	6,093	4,570	3,656	3,047	
Mower and Tractor							
Fixed Costs per Acre ($)	2.96	5.10	7.65	10.21	12.76	15.31	
Variable Costs per Acre ($)	1.52	2.06	3.13	4.12	5.15	6.26	
Mowing Harvest Unit							
Labor per Acre ($)	0.19	0.34	0.51	0.68	0.85	1.03	
Fixed Costs per Acre ($)	2.96	5.10	7.65	10.21	12.76	15.31	
Machine Variable Costs per Acre ($)	1.52	2.06	3.13	4.12	5.15	6.26	
Total Per Acre Costs ($)	4.67	7.50	11.29	15.01	18.76	22.60	
Total Annual Cost($/HU)	75,505	68,567	68,811	68,613	68,604	68,842	69,824

Note: A mowing harvest unit includes one laborer, one mower, and one tractor.

Table C-5. The Annual Operating Maintenance Cost of a Raking-Baling-Stacking Harvest Unit per Acre for the Least WD Model

	Yield per Acre (Tons)						
	1	2	3	4	5	6	Average
Annual Acres	48,469	27,420	18,280	13,710	10,968	9,140	
Transporter-Stacker							
Fixed Costs per Acre ($)	1.92	3.39	5.08	6.78	8.47	10.17	
Variable Costs per Acre ($)	0.36	0.64	0.97	1.29	1.61	1.93	
Rakes, Balers, Tractors							
Fixed Costs per Acre ($)	8.16	14.42	21.65	28.87	36.04	43.29	
Variable Costs per Acre ($)	3.66	5.62	8.65	11.23	12.42	15.34	
Raking-Baling-Stacking Harvest Unit							
Labor per Acre ($)	0.45	0.80	1.20	1.60	1.99	2.39	
Fixed Costs per Acre ($)	10.08	17.81	26.73	35.65	44.51	53.46	
Machine Variable Costs per Acre ($)	4.02	6.26	9.62	12.52	14.03	17.28	
Total Per Acre Costs ($)	14.55	24.87	37.55	49.77	60.53	73.12	
Total Annual Cost($/HU)	705,288	681,874	686,353	682,286	663,942	668,347	681,348

Note: A raking-baling-stacking harvest unit includes seven laborers, three rakes, three balers, six tractors, and a field stacker. Raking costs were added to yields of 4.5 tons per acre and greater. The costs were based on operating the rakes 20% of the time.

Table C-6. Daily Harvest Capacity in Terms of Acres and Tons for a Mowing Harvest Unit and a Raking-Baling-Stacking Harvest Unit

Yield (T/A)	Mower (1)			Rakes (3)			Balers (3)			Stacker (1)		
	A/H	A/D/M	T/D/M	A/H	A/D/M	T/D/M	A/H	A/D/M	T/D/M	A/H	A/D/M	T/D/M
1 ton	13.6	90	90	40.7	269	269	40.7	269	269	40.7	269	269
2 ton	9.7	64	128	38.4	254	508	23.3	154	308	23.1	153	305
3 ton	6.4	42	127	25.6	169	508	15.1	100	300	15.3	101	304
4 ton	4.9	32	128	19.2	127	508	11.6	77	308	11.4	76	303
5 ton	3.9	26	129	15.1	100	500	9.3	62	308	9.2	61	304
6 ton	3.2	21	127	12.8	85	508	7.6	50	300	7.7	51	304

Note: T/A is tons per acre, A/H is acres per hour, A/D/M is acres per day per harvest unit, and T/D/M is tons per day per harvest unit. A labor day is eight hours.

APPENDIX D -- SAS Code for Computing the Number of Baling Days

```
dm 'log;clear;output;clear;';
options pageno=1 formdlim='_' nodate linesize=80 pagesize=120;

%macro sm(name,num);
%let wstat=&name;
data sm_&wstat; set drying.sm_&wstat;
fc=&num;
mc=sm/fc*100;
run;
%mend sm;


%macro split(name);
%let wstat=&name;
%do i=1994 %to 2006;
dm 'log;clear;';
/* Split rain data by year */
data rain_&wstat&i; set drying.rain_&wstat;
if year ^=&i then delete;
run;
data rain_&wstat&i; set rain_&wstat&i;
rain&i=rain;
run;

/* Split soil moisture data by year */
data sm_&wstat&i; set sm_&wstat;
if year ^=&i then delete;
run;
data sm_&wstat&i; set sm_&wstat&i;
t=_n_;
run;
%end;
quit;
%mend split;

%macro split_sm1(name,year);
%let wstat=&name;
%let yr=&year;
%let r=_r;
%do i=1 %to 365;
dm 'log;clear;';
data &wstat&yr&r&i; set sm_&wstat&yr;
if t ^=&i then delete;
run;
%end;
quit;
%mend split_sm1;

%macro split_sm2(name,year);
%let wstat=&name;
%let yr=&year;
%let r=_r;
%do i=1 %to 366;
dm 'log;clear;';
data &wstat&yr&r&i; set sm_&wstat&yr;
if t ^=&i then delete;
run;
%end;
quit;
%mend split_sm2;

%macro split_sm3(name,year);
%let wstat=&name;
```

```
%let yr=&year;
%let r=_r;
%do i=1 %to 151;
dm 'log;clear;';
data &wstat&yr&r&i; set sm_&wstat&yr;
if t ^=&i then delete;
run;
%end;
quit;
%mend split_sm3;

%macro data1(name,year);
%let wstat=&name;
%let yr=&year;
%let drying=drying.;
data &wstat&yr; set &drying&wstat&yr;
obs=_n_;
gamma=((17.27*tair)/(237.7+tair))+log(relh/100);
tdew=(237.7*gamma)/(17.27-gamma);
satvp=0.6108*exp((17.27*tair)/(tair+237.3)); /*Saturation Vapor pressure*/
actvp=0.6108*exp((17.27*tdew)/(tdew+237.3)); /*Actual Vapor Pressure */
vpd=satvp-actvp; /* Vapor Pressure deficit */
if vpd <0 then vpd=0;
rh=relh/100; /*relative humidity (decimal)*/
wind=ws2m; /*average wind speed (2m), m/s */
si=srad; /*Solar radiation, W/m^2 */
swd=1587; /* Swath density */

/* Initial moisture content(%) of cut-grasses in dry base */
if month=1 then m0=15;
if month=2 then m0=15;
if month=3 then m0=15;
if month=4 then m0=75;
if month=5 then m0=70;
if month=6 then m0=65;
if month=7 then m0=62;
if month=8 then m0=60;
if month=9 then m0=58;
if month=10 then m0=55;
if month=11 then m0=15;
if month=12 then m0=15;

n1=15;   n2=39;   n3=63;   n4=87;   n5=111;  n6=135;  n7=159;  n8=183;  n9=207;
n10=231;
n11=255;  n12=279;  n13=303;  n14=327;  n15=351;  n16=375;  n17=399;  n18=423;
n19=447; n20=471;
n21=495;  n22=519;  n23=543;  n24=567;  n25=591;  n26=615;  n27=639;  n28=663;
n29=687; n30=711;
n31=735;

n32=759;  n33=783;  n34=807;  n35=831;  n36=855;  n37=879;  n38=903;  n39=927;
n40=951;  n41=975;
n42=999;  n43=1023; n44=1047; n45=1071; n46=1095; n47=1119; n48=1143; n49=1167;
n50=1191; n51=1215;
n52=1239; n53=1263; n54=1287; n55=1310; n56=1334; n57=1358; n58=1382; n59=1406;

n60=1430; n61=1454; n62=1478; n63=1502; n64=1526; n65=1550; n66=1574; n67=1598;
n68=1622; n69=1646;
n70=1670; n71=1694; n72=1718; n73=1742; n74=1766; n75=1790; n76=1814; n77=1838;
n78=1862; n79=1886;
n80=1910; n81=1934; n82=1958; n83=1982; n84=2006; n85=2030; n86=2054; n87=2078;
n88=2102; n89=2126;
n90=2150;
```

```
n91=2174;   n92=2198;   n93=2222;   n94=2246;   n95=2270;   n96=2294;   n97=2318;
n98=2342;  n99=2366;  n100=2390;
n101=2414;  n102=2437;  n103=2461;  n104=2485;  n105=2509;  n106=2533;  n107=2557;
n108=2581; n109=2605; n110=2629;
n111=2653;  n112=2677;  n113=2701;  n114=2725;  n115=2749;  n116=2773;  n117=2797;
n118=2821; n119=2845; n120=2869;

n121=2893;  n122=2917;  n123=2941;  n124=2965;  n125=2989;  n126=3013;  n127=3037;
n128=3061; n129=3085; n130=3109;
n131=3133;  n132=3157;  n133=3181;  n134=3205;  n135=3229;  n136=3253;  n137=3277;
n138=3301; n139=3325; n140=3349;
n141=3373;  n142=3397;  n143=3421;  n144=3445;  n145=3469;  n146=3493;  n147=3517;
n148=3541; n149=3565; n150=3589;
n151=3613;

n152=3637;  n153=3661;  n154=3685;  n155=3709;  n156=3733;  n157=3757;  n158=3781;
n159=3805; n160=3829; n161=3853;
n162=3877;  n163=3901;  n164=3925;  n165=3949;  n166=3973;  n167=3997;  n168=4021;
n169=4045; n170=4069; n171=4093;
n172=4117;  n173=4141;  n174=4165;  n175=4189;  n176=4213;  n177=4237;  n178=4261;
n179=4285; n180=4309; n181=4333;

n182=4357;  n183=4381;  n184=4405;  n185=4429;  n186=4453;  n187=4477;  n188=4501;
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n192=4597;  n193=4621;  n194=4645;  n195=4669;  n196=4693;  n197=4717;  n198=4741;
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n202=4837;  n203=4861;  n204=4885;  n205=4909;  n206=4933;  n207=4957;  n208=4981;
n209=5005; n210=5029; n211=5053;
n212=5077;

n213=5101;  n214=5125;  n215=5149;  n216=5173;  n217=5197;  n218=5221;  n219=5245;
n220=5269; n221=5293; n222=5317;
n223=5341;  n224=5365;  n225=5389;  n226=5413;  n227=5437;  n228=5461;  n229=5485;
n230=5509; n231=5533; n232=5557;
n233=5581;  n234=5605;  n235=5629;  n236=5653;  n237=5677;  n238=5701;  n239=5725;
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n254=6086;  n255=6110;  n256=6134;  n257=6158;  n258=6182;  n259=6206;  n260=6230;
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n264=6326;  n265=6350;  n266=6374;  n267=6398;  n268=6422;  n269=6446;  n270=6470;
n271=6494; n272=6518; n273=6542;

n274=6566;  n275=6590;  n276=6614;  n277=6638;  n278=6662;  n279=6686;  n280=6710;
n281=6734; n282=6758; n283=6782;
n284=6806;  n285=6830;  n286=6854;  n287=6878;  n288=6902;  n289=6926;  n290=6650;
n291=6974; n292=6998; n293=7022;
n294=7046;  n295=7070;  n296=7094;  n297=7118;  n298=7142;  n299=7166;  n300=7190;
n301=7214; n302=7238; n303=7262;
n304=7286;

n305=7310;  n306=7334;  n307=7358;  n308=7382;  n309=7406;  n310=7431;  n311=7455;
n312=7479; n313=7503; n314=7527;
n315=7551;  n316=7575;  n317=7599;  n318=7623;  n319=7647;  n320=7671;  n321=7695;
n322=7719; n323=7743; n324=7767;
n325=7791;  n326=7815;  n327=7839;  n328=7863;  n329=7887;  n330=7911;  n331=7935;
n332=7959; n333=7983; n334=8007;

n335=8031;  n336=8055;  n337=8079;  n338=8103;  n339=8127;  n340=8151;  n341=8175;
n342=8199; n343=8223; n344=8247;
```

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n345=8271; n346=8295; n347=8319; n348=8343; n349=8367; n350=8391; n351=8415;
n352=8439; n353=8463; n354=8487;
n355=8511; n356=8535; n357=8559; n358=8583; n359=8607; n360=8631; n361=8655;
n362=8679; n363=8703; n364=8727;
n365=8751; n366=8775;


d1=24;   d2=48;   d3=72;   d4=96;   d5=120;  d6=144;  d7=168;  d8=192;  d9=216;
d10=240;
d11=264;  d12=288;  d13=312;  d14=336;  d15=360;  d16=384;  d17=408;  d18=432;
d19=456; d20=480;
d21=504;  d22=528;  d23=552;  d24=576;  d25=600;  d26=624;  d27=648;  d28=672;
d29=696; d30=721;
d31=745;

d32=769;  d33=793;  d34=817;  d35=841;  d36=865;  d37=889;  d38=913;  d39=937;
d40=961;  d41=985;
d42=1009; d43=1033; d44=1057; d45=1081; d46=1105; d47=1129; d48=1153; d49=1177;
d50=1201; d51=1225;
d52=1249; d53=1273; d54=1297; d55=1321; d56=1345; d57=1369; d58=1393; d59=1417;

d60=1441; d61=1465; d62=1489; d63=1513; d64=1537; d65=1561; d66=1585; d67=1609;
d68=1633; d69=1657;
d70=1681; d71=1705; d72=1729; d73=1753; d74=1777; d75=1801; d76=1825; d77=1849;
d78=1873; d79=1897;
d80=1921; d81=1945; d82=1969; d83=1993; d84=2017; d85=2041; d86=2065; d87=2089;
d88=2113; d89=2137;
d90=2161;

d91=2185;   d92=2209;   d93=2233;   d94=2257;   d95=2281;   d96=2305;   d97=2329;
d98=2353;  d99=2377;  d100=2401;
d101=2425; d102=2449; d103=2474; d104=2498; d105=2522; d106=2546; d107=2570;
d108=2594; d109=2618; d110=2642;
d111=2666; d112=2690; d113=2714; d114=2738; d115=2762; d116=2786; d117=2810;
d118=2834; d119=2858; d120=2882;

d121=2906; d122=2930; d123=2954; d124=2978; d125=3002; d126=3026; d127=3050;
d128=3074; d129=3098; d130=3122;
d131=3146; d132=3170; d133=3194; d134=3218; d135=3242; d136=3266; d137=3290;
d138=3314; d139=3338; d140=3362;
d141=3386; d142=3410; d143=3434; d144=3458; d145=3482; d146=3506; d147=3530;
d148=3554; d149=3578; d150=3602;
d151=3626;

d152=3650; d153=3674; d154=3698; d155=3722; d156=3746; d157=3770; d158=3794;
d159=3818; d160=3842; d161=3866;
d162=3890; d163=3914; d164=3938; d165=3962; d166=3986; d167=4010; d168=4034;
d169=4058; d170=4082; d171=4106;
d172=4130; d173=4154; d174=4178; d175=4202; d176=4226; d177=4250; d178=4274;
d179=4298; d180=4322; d181=4346;

d182=4370; d183=4394; d184=4418; d185=4442; d186=4466; d187=4490; d188=4514;
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d192=4610; d193=4634; d194=4658; d195=4682; d196=4706; d197=4730; d198=4754;
d199=4778; d200=4802; d201=4826;
d202=4850; d203=4874; d204=4898; d205=4922; d206=4946; d207=4970; d208=4994;
d209=5018; d210=5042; d211=5066;
d212=5090;

d213=5114; d214=5138; d215=5162; d216=5186; d217=5210; d218=5234; d219=5258;
d220=5282; d221=5306; d222=5330;
d223=5354; d224=5378; d225=5402; d226=5426; d227=5450; d228=5474; d229=5498;
d230=5522; d231=5546; d232=5570;
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d233=5594; d234=5618; d235=5642; d236=5666; d237=5690; d238=5714; d239=5738; d240=5762; d241=5786; d242=5810;
d243=5834;

d244=5858; d245=5882; d246=5906; d247=5930; d248=5954; d249=5977; d250=6001; d251=6025; d252=6049; d253=6073;
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d264=6337; d265=6361; d266=6385; d267=6409; d268=6433; d269=6457; d270=6481; d271=6505; d272=6529; d273=6553;

d274=6577; d275=6601; d276=6625; d277=6649; d278=6673; d279=6697; d280=6721; d281=6745; d282=6769; d283=6793;
d284=6817; d285=6841; d286=6865; d287=6889; d288=6912; d289=6936; d290=6660; d291=6984; d292=7008; d293=7032;
d294=7056; d295=7080; d296=7104; d297=7128; d298=7152; d299=7176; d300=7200; d301=7224; d302=7248; d303=7272;
d304=7296;

d305=7320; d306=7344; d307=7368; d308=7392; d309=7416; d310=7440; d311=7464; d312=7488; d313=7512; d314=7536;
d315=7560; d316=7584; d317=7608; d318=7632; d319=7656; d320=7680; d321=7704; d322=7728; d323=7752; d324=7776;
d325=7800; d326=7824; d327=7848; d328=7872; d329=7896; d330=7920; d331=7944; d332=7968; d333=7992; d334=8016;

d335=8040; d336=8064; d337=8088; d338=8112; d339=8136; d340=8160; d341=8184; d342=8208; d343=8232; d344=8256;
d345=8280; d346=8304; d347=8328; d348=8352; d349=8376; d350=8400; d351=8424; d352=8448; d353=8472; d354=8496;
d355=8520; d356=8544; d357=8568; d358=8592; d359=8616; d360=8640; d361=8664; d362=8688; d363=8712; d364=8736;
d365=8760; d366=8784;

k1=39; k2=63; k3=87; k4=111; k5=135; k6= 159; k7=183; k8=207; k9=231;
k10=255; k11=279; k12=303; k13=327; k14=351; k15=375; k16=399; k17=423; k18=447; k19=471;
k20=495; k21=519; k22=543; k23=567; k24=591; k25=615; k26=639; k27=663; k28=687; k29=711;
k30=735;

k31=759; k32=783; k33=807; k34=831; k35=855; k36=879; k37=903; k38=927; k39=951; k40=975;
k41=999; k42=1023; k43=1047; k44=1071; k45=1095; k46=1119; k47=1143; k48=1167; k49=1191; k50=1215;
k51=1239; k52=1263; k53=1287; k54=1310; k55=1334; k56=1358; k57=1382; k58=1406;

k59=1430; k60=1454; k61=1478; k62=1502; k63=1526; k64=1550; k65=1574; k66=1598; k67=1622; k68=1646;
k69=1670; k70=1694; k71=1718; k72=1742; k73=1766; k74=1790; k75=1814; k76=1838; k77=1862; k78=1886;
k79=1910; k80=1934; k81=1958; k82=1982; k83=2006; k84=2030; k85=2054; k86=2078; k87=2102; k88=2126;
k89=2150;

k90=2174; k91=2198; k92=2222; k93=2246; k94=2270; k95=2294; k96=2318; k97=2342; k98=2366; k99=2390;
k100=2414; k101=2437; k102=2461; k103=2485; k104=2509; k105=2533; k106=2557; k107=2581; k108=2605; k109=2629;
k110=2653; k111=2677; k112=2701; k113=2725; k114=2749; k115=2773; k116=2797; k117=2821; k118=2845; k119=2869;

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k120=2893;  k121=2917;  k122=2941;  k123=2965;  k124=2989;  k125=3013;  k126=3037;
k127=3061; k128=3085; k129=3109;
k130=3133;  k131=3157;  k132=3181;  k133=3205;  k134=3229;  k135=3253;  k136=3277;
k137=3301; k138=3325; k139=3349;
k140=3373;  k141=3397;  k142=3421;  k143=3445;  k144=3469;  k145=3493;  k146=3517;
k147=3541; k148=3565; k149=3589;
k150=3613;

k151=3637;  k152=3661;  k153=3685;  k154=3709;  k155=3733;  k156=3757;  k157=3781;
k158=3805; k159=3829; k160=3853;
k161=3877;  k162=3901;  k163=3925;  k164=3949;  k165=3973;  k166=3997;  k167=4021;
k168=4045; k169=4069; k170=4093;
k171=4117;  k172=4141;  k173=4165;  k174=4189;  k175=4213;  k176=4237;  k177=4261;
k178=4285; k179=4309; k180=4333;

k181=4357;  k182=4381;  k183=4405;  k184=4429;  k185=4453;  k186=4477;  k187=4501;
k188=4525; k189=4549; k190=4573;
k191=4597;  k192=4621;  k193=4645;  k194=4669;  k195=4693;  k196=4717;  k197=4741;
k198=4765; k199=4789; k200=4813;
k201=4837;  k202=4861;  k203=4885;  k204=4909;  k205=4933;  k206=4957;  k207=4981;
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k212=5101;  k213=5125;  k214=5149;  k215=5173;  k216=5197;  k217=5221;  k218=5245;
k219=5269; k220=5293; k221=5317;
k222=5341;  k223=5365;  k224=5389;  k225=5413;  k226=5437;  k227=5461;  k228=5485;
k229=5509; k230=5533; k231=5557;
k232=5581;  k233=5605;  k234=5629;  k235=5653;  k236=5677;  k237=5701;  k238=5725;
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k243=5846;  k244=5870;  k245=5894;  k246=5918;  k247=5942;  k248=5966;  k249=5990;
k250=6014; k251=6038; k252=6062;
k253=6086;  k254=6110;  k255=6134;  k256=6158;  k257=6182;  k258=6206;  k259=6230;
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k263=6326;  k264=6350;  k265=6374;  k266=6398;  k267=6422;  k268=6446;  k269=6470;
k270=6494; k271=6518; k272=6542;

k273=6566;  k274=6590;  k275=6614;  k276=6638;  k277=6662;  k278=6686;  k279=6710;
k280=6734; k281=6758; k282=6782;
k283=6806;  k284=6830;  k285=6854;  k286=6878;  k287=6902;  k288=6926;  k289=6950;
k290=6974; k291=6998; k292=7022;
k293=7046;  k294=7070;  k295=7094;  k296=7118;  k297=7142;  k298=7166;  k299=7190;
k300=7214; k301=7238; k302=7262;
k303=7286;

k304=7310;  k305=7334;  k306=7358;  k307=7382;  k308=7406;  k309=7431;  k310=7455;
k311=7479; k312=7503; k313=7527;
k314=7551;  k315=7575;  k316=7599;  k317=7623;  k318=7647;  k319=7671;  k320=7695;
k321=7719; k322=7743; k323=7767;
k324=7791;  k325=7815;  k326=7839;  k327=7863;  k328=7887;  k329=7911;  k330=7935;
k331=7959; k332=7983; k333=8007;

k334=8031;  k335=8055;  k336=8079;  k337=8103;  k338=8127;  k339=8151;  k340=8175;
k341=8199; k342=8223; k343=8247;
k344=8271;  k345=8295;  k346=8319;  k347=8343;  k348=8367;  k349=8391;  k350=8415;
k351=8439; k352=8463; k353=8487;
k354=8511;  k355=8535;  k356=8559;  k357=8583;  k358=8607;  k359=8631;  k360=8655;
k361=8679; k362=8703; k363=8727;
k364=8751; k365=8775; k366=8799;

run;
%mend data1;
```

```
%macro nmean0(name,year);
%let wstat=&name;
%let yr=&year;
%let n0=_n0;
data &wstat&yr&n0; set &wstat&yr;
if obs>=n1 then delete;
run;

proc means data=&wstat&yr&n0 mean noprint;
var rh wind;
output out=&wstat&yr&n0 mean=;
run;
%mend nmean0;

%macro dmean1(name,year);
%let wstat=&name;
%let yr=&year;
%let d=_d;
%let r=_r;
%do i=1 %to 365;
dm 'log;clear;';
data &wstat&yr&d&i; set &wstat&yr;
if obs<n&i then delete;
if obs>d&i then delete;
t1=d&i-n&i-3;
t2=d&i-n&i+1; /* Drying interval */
t3=24-t2;
raind=rain;
proc means data=&wstat&yr&d&i mean noprint;
var year month day vpd si m0  swd raind t1 t2 t3 ;
output out=&wstat&yr&d&i mean=;
run;

data &wstat&yr&d&i; set &wstat&yr&d&i; set &wstat&yr&r&i;
dr1=(si+43.8*vpd)/((61.4*mc)+(swd*0.99*1.68)+2767);
if m0>15 then md1=m0/exp(1.04*dr1*t2); else md1=15;
if md1<15 then md1=15;
attrib working1 length=$3;
if md1>15 then working1="no"; else working1="yes";
/* md1=the moisture content of cutgrasss at sunset in the first day(%,db)*/
/* When moisture cuntent of cutgrass is 17.6%(d.b), farmers bale it. */
/*keep year month day mc vpd si m0  swd t1 t2 t3 dr1 md1 working1;*/
run;
quit;
%end;
%mend dmean1;

%macro dmean2(name,year);
%let wstat=&name;
%let yr=&year;
%let d=_d;
%let r=_r;
%do i=1 %to 366;
dm 'log;clear;';
data &wstat&yr&d&i; set &wstat&yr;
if obs<n&i then delete;
if obs>d&i then delete;
t1=d&i-n&i-3;
t2=d&i-n&i+1; /* Drying interval */
t3=24-t2;
raind=rain;
proc means data=&wstat&yr&d&i mean noprint;
```

```
var year month day vpd si m0  swd raind t1 t2 t3 ;
output out=&wstat&yr&d&i mean=;
run;

data &wstat&yr&d&i; set &wstat&yr&d&i; set &wstat&yr&r&i;
dr1=(si+43.8*vpd)/((61.4*mc)+(swd*0.99*1.68)+2767);
if m0>15 then md1=m0/exp(1.04*dr1*t2); else md1=15;
if md1<15 then md1=15;
attrib working1 length=$3;
if md1>15 then working1="no"; else working1="yes";
/* md1=the moisture content of cutgrasss at sunset in the first day(%,db)*/
/* When moisture cuntent of cutgrass is 17.6%(d.b), farmers bale it. */
/*keep year month day mc vpd si m0  swd t1 t2 t3 dr1 md1 working1;*/
run;
quit;
%end;
%mend dmean2;

%macro dmean3(name,year);
%let wstat=&name;
%let yr=&year;
%let d=_d;
%let r=_r;
%do i=1 %to 151;
dm 'log;clear;';
data &wstat&yr&d&i; set &wstat&yr;
if obs<n&i then delete;
if obs>d&i then delete;
t1=d&i-n&i-3;
t2=d&i-n&i+1; /* Drying interval */
t3=24-t2;
raind=rain;
proc means data=&wstat&yr&d&i mean noprint;
var year month day vpd si m0  swd raind t1 t2 t3 ;
output out=&wstat&yr&d&i mean=;
run;

data &wstat&yr&d&i; set &wstat&yr&d&i; set &wstat&yr&r&i;
dr1=(si+43.8*vpd)/((61.4*mc)+(swd*0.99*1.68)+2767);
if m0>15 then md1=m0/exp(1.04*dr1*t2); else md1=15;
if md1<15 then md1=15;
attrib working1 length=$3;
if md1>15 then working1="no"; else working1="yes";
/* md1=the moisture content of cutgrasss at sunset in the first day(%,db)*/
/* When moisture cuntent of cutgrass is 17.6%(d.b), farmers bale it. */
/*keep year month day mc vpd si m0  swd t1 t2 t3 dr1 md1 working1;*/
run;
quit;
%end;
%mend dmean3;

%macro nmean1(name,year);
%let wstat=&name;
%let yr=&year;
%let n=_n;
%let r=_r;
%do j=1 %to 365;
dm 'log;clear;';
data &wstat&yr&n&j; set &wstat&yr;
if obs<=d&j then delete;
if obs>=k&j then delete;

proc means data=&wstat&yr&n&j mean noprint;
```

```
var rh wind rain;
output out=&wstat&yr&n&j mean=;
run;
quit;
%end;
%mend nmean1;

%macro nmean2(name,year);
%let wstat=&name;
%let yr=&year;
%let n=_n;
%let r=_r;
%do j=1 %to 366;
dm 'log;clear;';
data &wstat&yr&n&j; set &wstat&yr;
if obs<=d&j then delete;
if obs>=k&j then delete;

proc means data=&wstat&yr&n&j mean noprint;
var rh wind rain;
output out=&wstat&yr&n&j mean=;
run;
quit;
%end;
%mend nmean2;

%macro nmean3(name,year);
%let wstat=&name;
%let yr=&year;
%let n=_n;
%let r=_r;
%do j=1 %to 151;
dm 'log;clear;';
data &wstat&yr&n&j; set &wstat&yr;
if obs<=d&j then delete;
if obs>=k&j then delete;

proc means data=&wstat&yr&n&j mean noprint;
var rh wind rain;
output out=&wstat&yr&n&j mean=;
run;
quit;
%end;
%mend nmean3;

%macro nd1(name,year);
%let wstat=&name;
%let yr=&year;
%let d=_d;
%let n=_n;
%let g=_g;

%do i=1 %to 365;
dm 'log;clear;';
data &wstat&yr&g&i; set &wstat&yr&d&i; set &wstat&yr&n&i;
if md1>15 then me1=exp(-2.5*(1-rh))*(0.4+(3.6*exp(-0.2*wind))); else me1=.;
if  rain=0  and   me1  ^=.  then  mf1=me1+(md1-me1)*(exp(-4*(t3/swd)));  else
mf1=4.0+(md1-4.0)*(exp(-150*((t3*rain)/swd)));
if me1=. then mf1=.;

/* Mf1= moisture content at the end of night in the first night(%,db)*/
/*keep year month day mc vpd si m0  swd t1 t2 t3 dr1 md1 working1 me1 mf1;*/
run;
```

```
/*proc print data=g&i;
run;
*/
quit;
%end;
%mend nd1;

%macro nd2(name,year);
%let wstat=&name;
%let yr=&year;
%let d=_d;
%let n=_n;
%let g=_g;

%do i=1 %to 366;
dm 'log;clear;';
data &wstat&yr&g&i; set &wstat&yr&d&i; set &wstat&yr&n&i;
if md1>15 then me1=exp(-2.5*(1-rh))*(0.4+(3.6*exp(-0.2*wind))); else me1=.;
if rain=0 and me1 ^=. then mf1=me1+(md1-me1)*(exp(-4*(t3/swd))); else
mf1=4.0+(md1-4.0)*(exp(-150*((t3*rain)/swd)));
if me1=. then mf1=.;

/* Mf1= moisture content at the end of night in the first night(%,db)*/
/*keep year month day mc vpd si m0  swd t1 t2 t3 dr1 md1 working1 me1 mf1;*/
run;

/*proc print data=g&i;
run;
*/
quit;
%end;
%mend nd2;

%macro nd3(name,year);
%let wstat=&name;
%let yr=&year;
%let d=_d;
%let n=_n;
%let g=_g;

%do i=1 %to 151;
dm 'log;clear;';
data &wstat&yr&g&i; set &wstat&yr&d&i; set &wstat&yr&n&i;
if md1>15 then me1=exp(-2.5*(1-rh))*(0.4+(3.6*exp(-0.2*wind))); else me1=.;
if rain=0 and me1 ^=. then mf1=me1+(md1-me1)*(exp(-4*(t3/swd))); else
mf1=4.0+(md1-4.0)*(exp(-150*((t3*rain)/swd)));
if me1=. then mf1=.;

/* Mf1= moisture content at the end of night in the first night(%,db)*/
/*keep year month day mc vpd si m0  swd t1 t2 t3 dr1 md1 working1 me1 mf1;*/
run;

/*proc print data=g&i;
run;
*/
quit;
%end;
%mend nd3;

%macro apd1(name,year);
%let wstat=&name;
%let yr=&year;
```

```
%let d=_d;
%let n=_n;
%let g=_g;
%let g1=_g1;

%do i=2 %to 366;
dm 'log;clear;';
proc datasets; append base=&wstat&yr&g1 data=&wstat&yr&g&i force;
run;
quit;
%end;
%mend apd1;

%macro apd2(name,year);
%let wstat=&name;
%let yr=&year;
%let d=_d;
%let n=_n;
%let g=_g;
%let g1=_g1;

%do i=2 %to 151;
dm 'log;clear;';
proc datasets; append base=&wstat&yr&g1 data=&wstat&yr&g&i force;
run;
quit;
%end;
%mend apd2;

%macro drying(name,year);
%let wstat=&name;
%let yr=&year;
%let dry1=_dry1;
/*%let n=_n;*/
/*%let g=_g;*/
%let g1=_g1;

%do i=&yr %to &yr;
/*data &wstat&yr&dry1; set &wstat&yr&g1;*/
data &wstat&i&dry1; set &wstat&i&g1;
lagmf1=lag(mf1);
if lagmf1 > 0  then dr2=(si+43.8*vpd)/((61.4*mc)+(swd*1.82*1.68)+2767); else
dr2=.;
if dr2>0 then md2=lagmf1/exp(1.04*dr2*t2); else md2=.;
attrib working2 length=$3;
if md2>15 then working2="no"; else working2="yes";
if md2=. then working2=' ';
if md2>15 then me2=exp(-2.5*(1-rh))*(0.4+(3.6*exp(-0.2*wind))); else me2=.;
if rain=0 and  me2 ^=. then mf2=me2+(md2-me2)*(exp(-4*(t3/swd))); else
mf2=4.0+(md2-4.0)*(exp(-150*((t3*rain)/swd)));
if me2=. then mf2=.;

lagmf2=lag(mf2);
if lagmf2 > 0  then dr3=(si+43.8*vpd)/((61.4*mc)+(swd*1.82*1.68)+2767); else
dr3=.;
if dr3>0 then md3=lagmf2/exp(1.04*dr3*t2); else md3=.;
attrib working3 length=$3;
if md3>15 then working3="no"; else working3="yes";
if md3=. then working3=' ';
if md3>15 then me3=exp(-2.5*(1-rh))*(0.4+(3.6*exp(-0.2*wind))); else me3=.;
if rain=0 and  me3 ^=. then mf3=me3+(md3-me3)*(exp(-4*(t3/swd))); else
mf3=4.0+(md3-4.0)*(exp(-150*((t3*rain)/swd)));
if me3=. then mf3=.;
```

```
lagmf3=lag(mf3);
if lagmf3 > 0 then dr4=(si+43.8*vpd)/((61.4*mc)+(swd*1.82*1.68)+2767); else
dr4=.;
if dr4>0 then md4=lagmf3/exp(1.04*dr4*t2); else md4=.;
attrib working4 length=$3;
if md4>15 then working4="no"; else working4="yes";
if md4=. then working4=' ';
if md4>15 then me4=exp(-2.5*(1-rh))*(0.4+(3.6*exp(-0.2*wind))); else me4=.;
if rain=0 and me4 ^=. then mf4=me4+(md4-me4)*(exp(-4*(t3/swd))); else
mf4=4.0+(md4-4.0)*(exp(-150*((t3*rain)/swd)));
if me4=. then mf4=.;

lagmf4=lag(mf4);
if lagmf4 > 0 then dr5=(si+43.8*vpd)/((61.4*mc)+(swd*1.82*1.68)+2767); else
dr5=.;
if dr5>0 then md5=lagmf4/exp(1.04*dr5*t2); else md5=.;
attrib working5 length=$3;
if md5>15 then working5="no"; else working5="yes";
if md5=. then working5=' ';
if md5>15 then me5=exp(-2.5*(1-rh))*(0.4+(3.6*exp(-0.2*wind))); else me5=.;
if rain=0 and me5 ^=. then mf5=me5+(md5-me5)*(exp(-4*(t3/swd))); else
mf5=4.0+(md5-4.0)*(exp(-150*((t3*rain)/swd)));
if me5=. then mf5=.;

lagmf5=lag(mf5);
if lagmf5 > 0 then dr6=(si+43.8*vpd)/((61.4*mc)+(swd*1.82*1.68)+2767); else
dr6=.;
if dr6>0 then md6=lagmf5/exp(1.04*dr6*t2); else md6=.;
attrib working6 length=$3;
if md6>15 then working6="no"; else working6="yes";
if md6=. then working6=' ';
if md6>15 then me6=exp(-2.5*(1-rh))*(0.4+(3.6*exp(-0.2*wind))); else me6=.;
if rain=0 and me6 ^=. then mf6=me6+(md6-me6)*(exp(-4*(t3/swd))); else
mf6=4.0+(md6-4.0)*(exp(-150*((t3*rain)/swd)));
if me6=. then mf6=.;

lagmf6=lag(mf6);
if lagmf6 > 0 then dr7=(si+43.8*vpd)/((61.4*mc)+(swd*1.82*1.68)+2767); else
dr7=.;
if dr7>0 then md7=lagmf6/exp(1.04*dr7*t2); else md7=.;
attrib working7 length=$3;
if md7>15 then working7="no"; else working7="yes";
if md7=. then working7=' ';
if md7>15 then me7=exp(-2.5*(1-rh))*(0.4+(3.6*exp(-0.2*wind))); else me7=.;
if rain=0 and me7 ^=. then mf7=me7+(md7-me7)*(exp(-4*(t3/swd))); else
mf7=4.0+(md7-4.0)*(exp(-150*((t3*rain)/swd)));
if me7=. then mf7=.;

lagmf7=lag(mf7);
if lagmf7 > 0 then dr8=(si+43.8*vpd)/((61.4*mc)+(swd*1.82*1.68)+2767); else
dr8=.;
if dr8>0 then md8=lagmf7/exp(1.04*dr8*t2); else md8=.;
attrib working8 length=$3;
if md8>15 then working8="no"; else working8="yes";
if md8=. then working8=' ';
if md8>15 then me8=exp(-2.5*(1-rh))*(0.4+(3.6*exp(-0.2*wind))); else me8=.;
if rain=0 and me8 ^=. then mf8=me8+(md8-me8)*(exp(-4*(t3/swd))); else
mf8=4.0+(md8-4.0)*(exp(-150*((t3*rain)/swd)));
if me8=. then mf8=.;

lagmf8=lag(mf8);
if lagmf8 > 0 then dr9=(si+43.8*vpd)/((61.4*mc)+(swd*1.82*1.68)+2767); else
```

```
dr9=.;
if dr9>0  then md9=lagmf8/exp(1.04*dr9*t2); else md9=.;
attrib working9 length=$3;
if md9>15 then working9="no"; else working9="yes";
if md9=. then working9=' ';
if md9>15 then me9=exp(-2.5*(1-rh))*(0.4+(3.6*exp(-0.2*wind))); else me9=.;
if  rain=0  and   me9  ^=.  then  mf9=me9+(md9-me9)*(exp(-4*(t3/swd)));  else
mf9=4.0+(md9-4.0)*(exp(-150*((t3*rain)/swd)));
if me9=. then mf9=.;

lagmf9=lag(mf9);
if lagmf9 > 0  then dr10=(si+43.8*vpd)/((61.4*mc)+(swd*1.82*1.68)+2767); else
dr10=.;
if dr10>0  then md10=lagmf9/exp(1.04*dr10*t2); else md10=.;
attrib working10 length=$3;
if md10>15 then working10="no"; else working10="yes";
if md10=. then working10=' ';
if md10>15 then me10=exp(-2.5*(1-rh))*(0.4+(3.6*exp(-0.2*wind))); else me10=.;
if rain=0 and  me10 ^=. then mf10=me10+(md10-me10)*(exp(-4*(t3/swd))); else
mf10=4.0+(md10-4.0)*(exp(-150*((t3*rain)/swd)));
if me10=. then mf10=.;

lagmf10=lag(mf10);
if lagmf10 > 0  then dr11=(si+43.8*vpd)/((61.4*mc)+(swd*1.82*1.68)+2767); else
dr11=.;
if dr11>0  then md11=lagmf10/exp(1.04*dr11*t2); else md11=.;
attrib working11 length=$3;
if md11>15 then working11="no"; else working11="yes";
if md11=. then working11=' ';
if md11>15 then me11=exp(-2.5*(1-rh))*(0.4+(3.6*exp(-0.2*wind))); else me11=.;
if rain=0 and  me11 ^=. then mf11=me11+(md11-me11)*(exp(-4*(t3/swd))); else
mf11=4.0+(md11-4.0)*(exp(-150*((t3*rain)/swd)));
if me11=. then mf11=.;

lagmf11=lag(mf11);
if lagmf11 > 0  then dr12=(si+43.8*vpd)/((61.4*mc)+(swd*1.82*1.68)+2767); else
dr12=.;
if dr12>0  then md12=lagmf11/exp(1.04*dr12*t2); else md12=.;
attrib working12 length=$3;
if md12>15 then working12="no"; else working12="yes";
if md12=. then working12=' ';
if md12>15 then me12=exp(-2.5*(1-rh))*(0.4+(3.6*exp(-0.2*wind))); else me12=.;
if rain=0 and  me12 ^=. then mf12=me12+(md12-me12)*(exp(-4*(t3/swd))); else
mf12=4.0+(md12-4.0)*(exp(-150*((t3*rain)/swd)));
if me12=. then mf12=.;
run;
%end;
%mend drying;


%macro data2(name,year);
%let wstat=&name;
%let yr=&year;
%let m=_m;
%let dry1=_dry1;

dm 'log;clear;';
%do i=1 %to 13;
data &wstat&yr&m&i; set &wstat&yr&dry1;
if month ^= &i then delete;
run;
%end;
quit;
```

```
%mend data2;


%macro result1(name,year);
%let wstat=&name;
%let yr=&year;
%let dry1=_dry1;

dm 'log;clear;';
/*ods html body='defaultmoments-body.htm';*/
%do i=1 %to 12;
proc print data=&wstat&yr&dry1;
var month day dr&i md&i working&i me&i mf&i;
run;
%end;
/*ods html close;*/
quit;
%mend result1;


%macro result2(name,year);
%let wstat=&name;
%let yr=&year;
%let m=_m;

dm 'log;clear;';
/*ods html body='defaultmoments-body.htm';*/
%do i=1 %to 12;
proc print data=&wstat&yr&m&i;
var year month day working1-working12;
run;
%end;
/*ods html close;*/
quit;
%mend result2;

%macro result3(name,year);
%let wstat=&name;
%let yr=&year;
%let out=out;
%let dry1=_dry1;

dm 'log;clear;';
data &wstat&yr&out; set &wstat&yr&dry1;
if working1="yes" then workday1=1; else workday1=0;
if working2="yes" then workday2=1; else workday2=0;
if working3="yes" then workday3=1; else workday3=0;
if working4="yes" then workday4=1; else workday4=0;
if working5="yes" then workday5=1; else workday5=0;
if working6="yes" then workday6=1; else workday6=0;
if working7="yes" then workday7=1; else workday7=0;
if working8="yes" then workday8=1; else workday8=0;
if working9="yes" then workday9=1; else workday9=0;
if working10="yes" then workday10=1; else workday10=0;
if working11="yes" then workday11=1; else workday11=0;
if working12="yes" then workday12=1; else workday12=0;
sum=workday1+workday2+workday3+workday4+workday5+workday6+workday7+workday8+wor
kday9+workday10+workday11+workday12;
attrib workday length=$3;
if sum=0 then workday="no"; else workday="yes";
keep year month day workday1-workday12 sum workday;
run;
```

```
/*ods html body='defaultmoments-body.htm';*/
proc print data=&wstat&yr&out;
run;
/*ods html close;*/
quit;
%mend result3;

%macro result4(name,year,num);
%let wstat=&name;
%let yr=&year;
%let tc=&num;
%let out=out;
%let a=_a;

dm 'log;clear;';
data &wstat&yr&out&a; set &wstat&yr&out; set sm_&wstat&yr; set rain_&wstat&yr;
attrib tract length=$3;
if mc>&tc then tract="no"; else tract="yes";
if tract="no" then tractindex=0; else tractindex=1;
if workday="no" then workindex=0; else workindex=1;
attrib bworkday length=$3;
if tract="no" and workday="no" then bworkday="no";
if tract="no" and workday="yes" then bworkday="no";
if tract="yes" and workday="no" then bworkday="no";
if tract="yes" and workday="yes" then bworkday="yes";
if bworkday="no" then bworkdayindex=0; else bworkdayindex=1;

attrib bworkday1 length=$3;
if rain&yr>0 and  bworkday="no" then bworkday1="no";
if rain&yr>0 and  bworkday="yes" then bworkday1="no";
if rain&yr=0 and  bworkday="no" then bworkday1="no";
if rain&yr=0 and  bworkday="yes" then bworkday1="yes";
run;

/*ods html body='defaultmoments-body.htm';*/
proc print data=&wstat&yr&out&a;
var year month day tract workday bworkday bworkday1;
run;
/*ods html close;*/
quit;
%mend result4;



%macro result5(name,year);
%let out=out;
%let wstat=&name;
%let yr=&year;
%let m=_m;
%let a=_a;

dm 'log;clear;';
%do i=1 %to 12;
data &wstat&yr&out&m&i; set &wstat&yr&out&a; set rain_&wstat&yr;
if month ^= &i then delete;
run;
%end;
quit;
%mend result5;

%macro result6(name,year);
%let out=out;
```

```
%let wstat=&name;
%let yr=&year;
%let m=_m;
%let a=_a;

dm 'log;clear;';
ods html body='defaultmoments-body.htm';
%do i=1 %to 12;
proc print data=&wstat&yr&out&m&i;
var year month day Rain&yr tract workday bworkday bworkday1;
run;
%end;
ods html close;
quit;
%mend result6;


%sm(beav, 37.5);
%split(beav);

%split_sm1(beav,1994);
%data1(beav,1994);
%nmean0(beav,1994);
%dmean1(beav,1994);
%nmean1(beav,1994);
%nd1(beav,1994);
%apd1(beav,1994);
%drying(beav,1994);
%data2(beav,1994);
%result1(beav,1994);
%result2(beav,1994);
%result3(beav,1994);
%result4(beav,1994,101);
%result5(beav,1994);
%result6(beav,1994);

%split_sm1(beav,1995);
%data1(beav,1995);
%nmean0(beav,1995);
%dmean1(beav,1995);
%nmean1(beav,1995);
%nd1(beav,1995);
%apd1(beav,1995);
%drying(beav,1995);
%data2(beav,1995);
%result1(beav,1995);
%result2(beav,1995);
%result3(beav,1995);
%result4(beav,1995,101);
%result5(beav,1995);
%result6(beav,1995);

%split_sm2(beav,1996);
%data1(beav,1996);
%nmean0(beav,1996);
%dmean2(beav,1996);
%nmean2(beav,1996);
%nd2(beav,1996);
%apd1(beav,1996);
%drying(beav,1996);
%data2(beav,1996);
%result1(beav,1996);
%result2(beav,1996);
```

```
%result3(beav,1996);
%result4(beav,1996,99);
%result5(beav,1996);
%result6(beav,1996);

%split_sm1(beav,1997);
%data1(beav,1997);
%nmean0(beav,1997);
%dmean1(beav,1997);
%nmean1(beav,1997);
%nd1(beav,1997);
%apd1(beav,1997);
%drying(beav,1997);
%data2(beav,1997);
%result1(beav,1997);
%result2(beav,1997);
%result3(beav,1997);
%result4(beav,1997,99);
%result5(beav,1997);
%result6(beav,1997);

%split_sm1(beav,1998);
%data1(beav,1998);
%nmean0(beav,1998);
%dmean1(beav,1998);
%nmean1(beav,1998);
%nd1(beav,1998);
%apd1(beav,1998);
%drying(beav,1998);
%data2(beav,1998);
%result1(beav,1998);
%result2(beav,1998);
%result3(beav,1998);
%result4(beav,1998,99);
%result5(beav,1998);
%result6(beav,1998);

%split_sm1(beav,1999);
%data1(beav,1999);
%nmean0(beav,1999);
%dmean1(beav,1999);
%nmean1(beav,1999);
%nd1(beav,1999);
%apd1(beav,1999);
%drying(beav,1999);
%data2(beav,1999);
%result1(beav,1999);
%result2(beav,1999);
%result3(beav,1999);
%result4(beav,1999,99);
%result5(beav,1999);
%result6(beav,1999);

%split_sm2(beav,2000);
%data1(beav,2000);
%nmean0(beav,2000);
%dmean2(beav,2000);
%nmean2(beav,2000);
%nd2(beav,2000);
%apd1(beav,2000);
%drying(beav,2000);
%data2(beav,2000);
%result1(beav,2000);
```

```
%result2(beav,2000);
%result3(beav,2000);
%result4(beav,2000,99);
%result5(beav,2000);
%result6(beav,2000);

%split_sm1(beav,2001);
%data1(beav,2001);
%nmean0(beav,2001);
%dmean1(beav,2001);
%nmean1(beav,2001);
%nd1(beav,2001);
%apd1(beav,2001);
%drying(beav,2001);
%data2(beav,2001);
%result1(beav,2001);
%result2(beav,2001);
%result3(beav,2001);
%result4(beav,2001,99);
%result5(beav,2001);
%result6(beav,2001);

%split_sm1(beav,2002);
%data1(beav,2002);
%nmean0(beav,2002);
%dmean1(beav,2002);
%nmean1(beav,2002);
%nd1(beav,2002);
%apd1(beav,2002);
%drying(beav,2002);
%data2(beav,2002);
%result1(beav,2002);
%result2(beav,2002);
%result3(beav,2002);
%result4(beav,2002,99);
%result5(beav,2002);
%result6(beav,2002);

%split_sm1(beav,2003);
%data1(beav,2003);
%nmean0(beav,2003);
%dmean1(beav,2003);
%nmean1(beav,2003);
%nd1(beav,2003);
%apd1(beav,2003);
%drying(beav,2003);
%data2(beav,2003);
%result1(beav,2003);
%result2(beav,2003);
%result3(beav,2003);
%result4(beav,2003,99);
%result5(beav,2003);
%result6(beav,2003);

%split_sm2(beav,2004);
%data1(beav,2004);
%nmean0(beav,2004);
%dmean2(beav,2004);
%nmean2(beav,2004);
%nd2(beav,2004);
%apd1(beav,2004);
%drying(beav,2004);
%data2(beav,2004);
```

```
%result1(beav,2004);
%result2(beav,2004);
%result3(beav,2004);
%result4(beav,2004,99);
%result5(beav,2004);
%result6(beav,2004);

%split_sm1(beav,2005);
%data1(beav,2005);
%nmean0(beav,2005);
%dmean1(beav,2005);
%nmean1(beav,2005);
%nd1(beav,2005);
%apd1(beav,2005);
%drying(beav,2005);
%data2(beav,2005);
%result1(beav,2005);
%result2(beav,2005);
%result3(beav,2005);
%result4(beav,2005,99);
%result5(beav,2005);
%result6(beav,2005);

%split_sm3(beav,2006);
%data1(beav,2006);
%nmean0(beav,2006);
%dmean3(beav,2006);
%nmean3(beav,2006);
%nd3(beav,2006);
%apd2(beav,2006);
%drying(beav,2006);
%data2(beav,2006);
%result1(beav,2006);
%result2(beav,2006);
%result3(beav,2006);
%result4(beav,2006,99);
%result5(beav,2006);
%result6(beav,2006);

quit;
```

APPENDIX E -- GAMS/CPLEX Code for the Base WD 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,WCENTR,SWEST,NCENTR,CENTR,SCENTR,NEAST,ECENTR,SEAST/

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

 JR(J,R) Prospective plant locations by region
   /Pontotoc.SCENTR, (Jackson, Comanche).SWEST, Washing.NEAST, Okmulgee.ECENTR,
    (Canadian,Payne).CENTR,(Garfield, Woodward).NCENTR, Custer.WCENTR, Texas.PANHAND/

 K Lignocellulosic feedstocks
   /Switchgr/

 CRS(K) "Crop residues and switchgrass"
   /Switchgr/

 KF Lignocellulosic biomass differentiated by fertility program
   /Switchg/

 KKF(K,KF) Allocating fertility subactivities to biomass activities
```

```
  /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
  /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).Switchgr/

 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, 2000)                                    *
**********************************************************************

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, 2000)                                         *
*********************************************************************

PARAMETER CAP21(FT) "Processing/storage capacity for 10.5 m gal plant"
   /STORAGE     21000
    PROCESS  21000000 /;

PARAMETER CAP(S,FT) Storage and processing capacity by plant size;
   CAP(S,FT)$(ORD(S) EQ 2) = CAP21(FT);
   CAP(S,FT)$(ORD(S) EQ 1) = CAP21(FT)*CAPADJ;
```

```
   CAP(S,FT)$(ORD(S) EQ 3) = CAP21(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, 2000)     *
**Construction of a corresponding storage facility is estimated     *
**  to cost about $1,528,846 (Huhnke, 2000)                         *
*********************************************************************

PARAMETER FC42(FT) "Construction costs for 50 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    1.76
   CO2      -24.70
   N2      -246.40
   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;
```

```
*******************************************************************
**Price of Nitrogen(PN)and level of nitrogen per acre(NIT) were    *
** obtained from:                                                   *
**      Personal communication with Dr.Huhnke and Dr.Epplin (2007) *
*******************************************************************

SCALAR PN "Price of nitrogen in $ per lb" /0.28/;

PARAMETER NIT(KF) Level of nitrogen by fertility program in lb per acre
  /Switchg  80 /;

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
Switchgr  0    0    0    0   1.00  1.00  1.00  0.95  0.90  0.85  0.80  0.75
;

*******************************************************************
**THETAI(K)and THETAK(K) were obtained from:                       *
**      Personal communication with Dr.Huhnke(2007)                *
** Storage loss at the field and bioreinery were assumed to be 1%. *
*******************************************************************

PARAMETER THETAI(K) Usable proportion of stored biomass at the source
/Switchgr  0.99    /;

PARAMETER THETAJ(K) Usable proportion of stored biomass at the plant
/  Switchgr  0.99    /;

PARAMETER GAMMA(K) Biomass storage cost at source in USD per ton (Huhnke)
/ Switchgr  2.00    /;

PARAMETER PSI(K) Biomass purchase cost in USD per ton
/ Switchgr  0.00    /;

*******************************************************************
**The estiblishment and maintenance cost of switchgrass were       *
** obtained from:                                                   *
** Switchgrass budgets model prepared by Dr.Epplin and Hwang       *
**The Land rent cost,$60 was determined by personel communication  *
** with Dr.Epplin.
*******************************************************************

TABLE POC(K,BC) "Biomass production and opportunity costs in $ per acre"
               Estcost   Maincost   Landrent   Biopcost
  Switchgr     26.00       3.00      60.00         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

             Switchgr
Adair           0
Alfalfa         0
Atoka           0
Beaver          0
Beckham         0
Blaine          0
Bryan           0
Caddo           0
Canadian        0
Carter          0
Cherokee        0
Choctaw         0
Cimarron        0
Clevelan        0
Coal            0
Comanche        0
```

```
Cotton          0
Craig           0
Creek           0
Custer          0
Delaware        0
Dewey           0
Ellis           0
Garfield        0
Garvin          0
Grady           0
Grant           0
Greer           0
Harmon          0
Harper          0
Haskell         0
Hughes          0
Jackson         0
Jeffers         0
Johnston        0
Kay             0
Kingfish        0
Kiowa           0
LeFlore         0
Lincoln         0
Logan           0
Love            0
Major           0
Marshall        0
Mayes           0
McClain         0
McCurt          0
McIntosh        0
Murray          0
Muskogee        0
Noble           0
Nowata          0
Okfuskee        0
Oklahoma        0
Okmulgee        0
Osage           0
Ottawa          0
Pawnee          0
Payne           0
Pittsbur        0
Pontotoc        0
Pottawat        0
RogerMil        0
Rogers          0
Seminole        0
Sequoyah        0
Stephens        0
Texas           0
Tillman         0
Tulsa           0
Wagoner         0
Washing         0
Washita         0
Woods           0
Woodward        0
;

TABLE CCURACRE(I,K) Current acreage for each biomass type on CRP Land
             Switchgr
Adair           0
Alfalfa         0
Atoka           0
Beaver          0
Beckham         0
Blaine          0
Bryan           0
Caddo           0
```

```
Canadian         0
Carter           0
Cherokee         0
Choctaw          0
Cimarron         0
Clevelan         0
Coal             0
Comanche         0
Cotton           0
Craig            0
Creek            0
Custer           0
Delaware         0
Dewey            0
Ellis            0
Garfield         0
Garvin           0
Grady            0
Grant            0
Greer            0
Harmon           0
Harper           0
Haskell          0
Hughes           0
Jackson          0
Jeffers          0
Johnston         0
Kay              0
Kingfish         0
Kiowa            0
LeFlore          0
Lincoln          0
Logan            0
Love             0
Major            0
Marshall         0
Mayes            0
McClain          0
McCurt           0
McIntosh         0
Murray           0
Muskogee         0
Noble            0
Nowata           0
Okfuskee         0
Oklahoma         0
Okmulgee         0
Osage            0
Ottawa           0
Pawnee           0
Payne            0
Pittsbur         0
Pontotoc         0
Pottawat         0
RogerMil         0
Rogers           0
Seminole         0
Sequoyah         0
Stephens         0
Texas            0
Tillman          0
Tulsa            0
Wagoner          0
Washing          0
Washita          0
Woods            0
Woodward         0
;

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
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
;

*******************************************************************
**Yield estimates for switchgrass were based upon estimates provided *
**by Graham, Allison, and Becker (1996) and Fuentes and Taliaferro   *
**(2002).                                                           *
** Fuentes, R.G., and C.M. Taliaferro.  2002.                       *
**"Biomass Yield Stability of Switchgrass Cultivars."               *
**In J. Janick and A. Whipkey, eds. Trends in New Crops and New Uses.*
**Alexandria, VA.:  ASHS Press, pp. 276-282.                        *
**Graham, R.L., L.J. Allison, and D.A. Becker.  1996.               *
**"The Oak Ridge Crop County Level Database." Environmental Sciences *
**Division, Bioenergy Feedstock Development Program, Oak Ridge      *
**National Laboratory, December.                                    *
*******************************************************************

TABLE BIOYLD1(I,KF) Biomass yield in lbs per acre
          Switchg
Adair      13000
Alfalfa    10000
Atoka      13000
Beaver         0
Beckham        0
Blaine     10000
Bryan      12000
Caddo      12000
Canadian   10000
Carter     12000
Cherokee   13000
Choctaw    12000
Cimarron       0
Clevelan   10000
Coal       12000
Comanche       0
Cotton         0
Craig      12000
Creek      12000
Custer         0
Delaware   13000
Dewey          0
Ellis          0
Garfield   10000
Garvin     10000
Grady      10000
Grant      10000
Greer          0
Harmon         0
Harper         0
Haskell    13000
Hughes     13000
Jackson        0
Jeffers    10000
Johnston   12000
Kay        10000
Kingfish   10000
Kiowa          0
LeFlore    13000
Lincoln    12000
Logan      10000
Love       12000
Major          0
Marshall   12000
Mayes      12000
McClain    10000
McCurt     13000
McIntosh   13000
Murray     12000
```

```
Muskogee   12000
Noble      10000
Nowata     12000
Okfuskee   12000
Oklahoma   12000
Okmulgee   12000
Osage      12000
Ottawa     12000
Pawnee     10000
Payne      10000
Pittsbur   13000
Pontotoc   12000
Pottawat   10000
RogerMil     0
Rogers     12000
Seminole   12000
Sequoyah   13000
Stephens   12000
Texas        0
Tillman      0
Tulsa      12000
Wagoner    12000
Washing    12000
Washita      0
Woods        0
Woodward     0
;
```

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
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
Hughes	174	88	126	244	173
Jackson	90	268	235	166	118

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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: The results for the number of mowing days and  *
** the number of baling days from this study                                      *
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TABLE FWD(I,M) Field-Workdays for Mowing Available in Oklahoma by county and month
               Mar     Apr     May     Jun     Jul     Aug     Sep
Adair          18.00   16.00   15.00   16.00   20.00   19.00   17.00
Alfalfa        16.00   15.00   17.00   16.00   17.00   18.00   20.00
Atoka          18.00   14.00   14.00   15.00   17.00   19.00   16.00
Beaver         17.00   16.00   15.00   15.00   17.00   15.00   19.00
Beckham        18.00   17.00   15.00   14.00   19.00   15.00   16.00
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Blaine	18.00	17.00	15.00	14.00	19.00	15.00	16.00
Bryan	18.00	14.00	14.00	15.00	17.00	19.00	16.00
Caddo	19.00	15.00	15.00	11.00	20.00	15.00	15.00
Canadian	16.00	17.00	16.00	14.00	19.00	17.00	18.00
Carter	18.00	14.00	14.00	15.00	17.00	19.00	16.00
Cherokee	18.00	16.00	15.00	16.00	20.00	19.00	17.00
Choctaw	15.00	11.00	16.00	12.00	18.00	18.00	18.00
Cimarron	17.00	16.00	15.00	15.00	17.00	15.00	19.00
Clevelan	16.00	17.00	16.00	14.00	19.00	17.00	18.00
Coal	18.00	14.00	14.00	15.00	17.00	19.00	16.00
Comanche	19.00	15.00	15.00	11.00	20.00	15.00	15.00
Cotton	19.00	15.00	15.00	11.00	20.00	15.00	15.00
Craig	12.00	16.00	16.00	11.00	16.00	20.00	17.00
Creek	16.00	17.00	16.00	14.00	19.00	17.00	18.00
Custer	18.00	17.00	15.00	14.00	19.00	15.00	16.00
Delaware	12.00	16.00	16.00	11.00	16.00	20.00	17.00
Dewey	18.00	17.00	15.00	14.00	19.00	15.00	16.00
Ellis	17.00	16.00	15.00	15.00	17.00	15.00	19.00
Garfield	16.00	15.00	17.00	16.00	17.00	18.00	20.00
Garvin	18.00	14.00	14.00	15.00	17.00	19.00	16.00
Grady	16.00	17.00	16.00	14.00	19.00	17.00	18.00
Grant	16.00	15.00	17.00	16.00	17.00	18.00	20.00
Greer	19.00	15.00	15.00	11.00	20.00	15.00	15.00
Harmon	19.00	15.00	15.00	11.00	20.00	15.00	15.00
Harper	17.00	16.00	15.00	15.00	17.00	15.00	19.00
Haskell	18.00	16.00	15.00	16.00	20.00	19.00	17.00
Hughes	18.00	16.00	15.00	16.00	20.00	19.00	17.00
Jackson	19.00	15.00	15.00	11.00	20.00	15.00	15.00
Jeffers	18.00	14.00	14.00	15.00	17.00	19.00	16.00
Johnston	18.00	14.00	14.00	15.00	17.00	19.00	16.00
Kay	16.00	15.00	17.00	16.00	17.00	18.00	20.00
Kingfish	16.00	17.00	16.00	14.00	19.00	17.00	18.00
Kiowa	19.00	15.00	15.00	11.00	20.00	15.00	15.00
LeFlore	15.00	11.00	16.00	12.00	18.00	18.00	14.00
Lincoln	16.00	17.00	16.00	14.00	19.00	17.00	18.00
Logan	16.00	17.00	16.00	14.00	19.00	17.00	18.00
Love	18.00	14.00	14.00	15.00	17.00	19.00	16.00
Major	16.00	15.00	17.00	16.00	17.00	18.00	20.00
Marshall	18.00	14.00	14.00	15.00	17.00	19.00	16.00
Mayes	12.00	16.00	16.00	11.00	16.00	20.00	17.00
McClain	16.00	17.00	16.00	14.00	19.00	17.00	18.00
McCurt	15.00	11.00	16.00	12.00	18.00	18.00	18.00
McIntosh	18.00	16.00	15.00	16.00	20.00	19.00	17.00
Murray	18.00	14.00	14.00	15.00	17.00	19.00	16.00
Muskogee	18.00	16.00	15.00	16.00	20.00	19.00	17.00
Noble	16.00	15.00	17.00	16.00	17.00	18.00	20.00
Nowata	12.00	16.00	16.00	11.00	16.00	20.00	17.00
Okfuskee	16.00	17.00	16.00	14.00	19.00	17.00	18.00
Oklahoma	16.00	17.00	16.00	14.00	19.00	17.00	18.00
Okmulgee	18.00	16.00	15.00	16.00	20.00	19.00	17.00
Osage	12.00	16.00	16.00	11.00	16.00	20.00	17.00
Ottawa	12.00	16.00	16.00	11.00	16.00	20.00	17.00
Pawnee	12.00	16.00	16.00	11.00	16.00	20.00	17.00
Payne	16.00	17.00	16.00	14.00	19.00	17.00	18.00
Pittsbur	18.00	16.00	15.00	16.00	20.00	19.00	17.00
Pontotoc	18.00	14.00	14.00	15.00	17.00	19.00	16.00
Pottawat	16.00	17.00	16.00	14.00	19.00	17.00	18.00
RogerMil	18.00	17.00	15.00	14.00	19.00	15.00	16.00
Rogers	12.00	16.00	16.00	11.00	16.00	20.00	17.00
Seminole	16.00	17.00	16.00	14.00	19.00	17.00	18.00
Sequoyah	18.00	16.00	15.00	16.00	20.00	19.00	17.00
Stephens	18.00	14.00	14.00	15.00	17.00	19.00	16.00
Texas	17.00	16.00	15.00	17.00	15.00	19.00	16.00
Tillman	19.00	15.00	15.00	11.00	20.00	15.00	15.00
Tulsa	12.00	16.00	16.00	11.00	16.00	20.00	17.00
Wagoner	12.00	16.00	16.00	11.00	16.00	20.00	17.00
Washing	12.00	16.00	16.00	11.00	16.00	20.00	17.00
Washita	18.00	17.00	15.00	14.00	19.00	15.00	16.00
Woods	16.00	15.00	17.00	16.00	17.00	18.00	20.00
Woodward	16.00	15.00	17.00	16.00	17.00	18.00	20.00

+	Oct	Nov	Dec	Jan	Feb
Adair	17.00	9.00	15.00	17.00	10.00
Alfalfa	17.00	14.00	15.00	18.00	18.00
Atoka	13.00	13.00	16.00	13.00	9.00
Beaver	16.00	10.00	21.00	21.00	15.00
Beckham	17.00	12.00	19.00	18.00	17.00
Blaine	17.00	12.00	19.00	18.00	17.00
Bryan	13.00	13.00	16.00	13.00	9.00
Caddo	15.00	14.00	19.00	16.00	16.00
Canadian	16.00	11.00	18.00	19.00	18.00
Carter	13.00	13.00	16.00	13.00	9.00
Cherokee	17.00	9.00	15.00	17.00	10.00
Choctaw	14.00	13.00	12.00	15.00	12.00
Cimarron	16.00	10.00	21.00	21.00	15.00
Clevelan	16.00	11.00	18.00	19.00	18.00
Coal	13.00	13.00	16.00	13.00	9.00
Comanche	15.00	14.00	19.00	16.00	16.00
Cotton	15.00	14.00	19.00	16.00	16.00
Craig	16.00	14.00	18.00	16.00	16.00
Creek	16.00	11.00	18.00	19.00	18.00
Custer	17.00	12.00	19.00	18.00	17.00
Delaware	16.00	14.00	18.00	16.00	16.00
Dewey	17.00	12.00	19.00	18.00	17.00
Ellis	16.00	10.00	21.00	21.00	15.00
Garfield	17.00	14.00	15.00	18.00	18.00
Garvin	13.00	13.00	16.00	13.00	9.00
Grady	16.00	11.00	18.00	19.00	18.00
Grant	17.00	14.00	15.00	18.00	18.00
Greer	15.00	14.00	19.00	16.00	16.00
Harmon	15.00	14.00	19.00	16.00	16.00
Harper	16.00	10.00	21.00	21.00	15.00
Haskell	17.00	9.00	15.00	17.00	10.00
Hughes	17.00	9.00	15.00	17.00	10.00
Jackson	15.00	14.00	19.00	16.00	16.00
Jeffers	13.00	13.00	16.00	13.00	9.00
Johnston	13.00	13.00	16.00	13.00	9.00
Kay	17.00	14.00	15.00	18.00	18.00
Kingfish	16.00	11.00	18.00	19.00	18.00
Kiowa	15.00	14.00	19.00	16.00	16.00
LeFlore	14.00	13.00	12.00	15.00	12.00
Lincoln	16.00	11.00	18.00	19.00	18.00
Logan	16.00	11.00	18.00	19.00	18.00
Love	13.00	13.00	16.00	13.00	9.00
Major	17.00	14.00	15.00	18.00	18.00
Marshall	13.00	13.00	16.00	13.00	9.00
Mayes	16.00	14.00	18.00	16.00	16.00
McClain	16.00	11.00	18.00	19.00	18.00
McCurt	14.00	13.00	12.00	15.00	12.00
McIntosh	17.00	9.00	15.00	17.00	10.00
Murray	13.00	13.00	16.00	13.00	9.00
Muskogee	17.00	9.00	15.00	17.00	10.00
Noble	17.00	14.00	15.00	18.00	18.00
Nowata	16.00	14.00	18.00	16.00	16.00
Okfuskee	16.00	11.00	18.00	19.00	18.00
Oklahoma	16.00	11.00	18.00	19.00	18.00
Okmulgee	17.00	9.00	15.00	17.00	10.00
Osage	16.00	14.00	18.00	16.00	16.00
Ottawa	16.00	14.00	18.00	16.00	16.00
Pawnee	16.00	14.00	18.00	16.00	16.00
Payne	16.00	11.00	18.00	19.00	18.00
Pittsbur	17.00	9.00	15.00	17.00	10.00
Pontotoc	13.00	13.00	16.00	13.00	9.00
Pottawat	16.00	11.00	18.00	19.00	18.00
RogerMil	17.00	12.00	19.00	18.00	17.00
Rogers	16.00	14.00	18.00	16.00	16.00
Seminole	16.00	11.00	18.00	19.00	18.00
Sequoyah	17.00	9.00	15.00	17.00	10.00
Stephens	13.00	13.00	16.00	13.00	9.00
Texas	16.00	10.00	21.00	21.00	15.00
Tillman	15.00	14.00	19.00	16.00	16.00
Tulsa	16.00	14.00	18.00	16.00	16.00

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Wagoner         16.00   14.00   18.00   16.00   16.00
Washing         16.00   14.00   18.00   16.00   16.00
Washita         17.00   12.00   19.00   18.00   17.00
Woods           17.00   14.00   15.00   18.00   18.00
Woodward        17.00   14.00   15.00   18.00   18.00
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TABLE BWD(I,M) Field Workdays for Baling Available in Oklahoma by county and month
                Mar     Apr     May     Jun     Jul     Aug     Sep
Adair           17.00    9.00    9.00   10.00   16.00   15.00    9.00
Alfalfa         14.00   11.00   11.00   13.00   16.00   14.00   13.00
Atoka           17.00    8.00    9.00   11.00   15.00   14.00   12.00
Beaver          17.00    9.00    8.00   11.00   15.00   14.00   11.00
Beckham         18.00   11.00   10.00    8.00   16.00   12.00    8.00
Blaine          18.00   11.00   10.00    8.00   16.00   12.00    8.00
Bryan           17.00    8.00    9.00   11.00   15.00   14.00   12.00
Caddo           19.00   10.00    9.00    8.00   15.00    9.00    8.00
Canadian        16.00   10.00   10.00   10.00   16.00   14.00   12.00
Carter          17.00    8.00    9.00   11.00   15.00   14.00   12.00
Cherokee        17.00    9.00    9.00   10.00   16.00   15.00    9.00
Choctaw         15.00    5.00    8.00    4.00   16.00   13.00   11.00
Cimarron        17.00    9.00    8.00   11.00   15.00   14.00   11.00
Clevelan        16.00   10.00   10.00   10.00   16.00   14.00   12.00
Coal            17.00    8.00    9.00   11.00   15.00   14.00   12.00
Comanche        19.00   10.00    9.00    8.00   15.00    9.00    8.00
Cotton          19.00   10.00    9.00    8.00   15.00    9.00    8.00
Craig           12.00    8.00   10.00    8.00   13.00   12.00    9.00
Creek           16.00   10.00   10.00   10.00   16.00   14.00   12.00
Custer          18.00   11.00   10.00    8.00   16.00   12.00    8.00
Delaware        12.00    8.00   10.00    8.00   13.00   12.00    9.00
Dewey           18.00   11.00   10.00    8.00   16.00   12.00    8.00
Ellis           17.00    9.00    8.00   11.00   15.00   14.00   11.00
Garfield        14.00   11.00   11.00   13.00   16.00   14.00   13.00
Garvin          17.00    8.00    9.00   11.00   15.00   14.00   12.00
Grady           16.00   10.00   10.00   10.00   16.00   14.00   12.00
Grant           14.00   11.00   11.00   13.00   16.00   14.00   13.00
Greer           19.00   10.00    9.00    8.00   15.00    9.00    8.00
Harmon          19.00   10.00    9.00    8.00   15.00    9.00    8.00
Harper          17.00    9.00    8.00   11.00   15.00   14.00   11.00
Haskell         17.00    9.00    9.00   10.00   16.00   15.00    9.00
Hughes          17.00    9.00    9.00   10.00   16.00   15.00    9.00
Jackson         19.00   10.00    9.00    8.00   15.00    9.00    8.00
Jeffers         17.00    8.00    9.00   11.00   15.00   14.00   12.00
Johnston        17.00    8.00    9.00   11.00   15.00   14.00   12.00
Kay             14.00   11.00   11.00   13.00   16.00   14.00   13.00
Kingfish        16.00   10.00   10.00   10.00   16.00   14.00   12.00
Kiowa           19.00   10.00    9.00    8.00   15.00    9.00    8.00
LeFlore         15.00    5.00    8.00    4.00   16.00   13.00   11.00
Lincoln         16.00   10.00   10.00   10.00   16.00   14.00   12.00
Logan           16.00   10.00   10.00   10.00   16.00   14.00   12.00
Love            17.00    8.00    9.00   11.00   15.00   14.00   12.00
Major           14.00   11.00   11.00   13.00   16.00   14.00   13.00
Marshall        17.00    8.00    9.00   11.00   15.00   14.00   12.00
Mayes           12.00    8.00   10.00    8.00   13.00   12.00    9.00
McClain         16.00   10.00   10.00   10.00   16.00   14.00   12.00
McCurt          15.00    5.00    8.00    4.00   16.00   13.00   11.00
McIntosh        17.00    9.00    9.00   10.00   16.00   15.00    9.00
Murray          17.00    8.00    9.00   11.00   15.00   14.00   12.00
Muskogee        17.00    9.00    9.00   10.00   16.00   15.00    9.00
Noble           14.00   11.00   11.00   13.00   16.00   14.00   13.00
Nowata          12.00    8.00   10.00    8.00   13.00   12.00    9.00
Okfuskee        16.00   10.00   10.00   10.00   16.00   14.00   12.00
Oklahoma        16.00   10.00   10.00   10.00   16.00   14.00   12.00
Okmulgee        17.00    9.00    9.00   10.00   16.00   15.00    9.0
Osage           12.00    8.00   10.00    8.00   13.00   12.00    9.00
Ottawa          12.00    8.00   10.00    8.00   13.00   12.00    9.00
Pawnee          12.00    8.00   10.00    8.00   13.00   12.00    9.00
Payne           16.00   10.00   10.00   10.00   16.00   14.00   12.00
Pittsbur        17.00    9.00    9.00   10.00   16.00   15.00    9.0
Pontotoc        17.00    8.00    9.00   11.00   15.00   14.00   12.00
Pottawat        16.00   10.00   10.00   10.00   16.00   14.00   12.00
```

RogerMil	18.00	11.00	10.00	8.00	16.00	12.00	8.00
Rogers	12.00	8.00	10.00	8.00	13.00	12.00	9.00
Seminole	16.00	10.00	10.00	10.00	16.00	14.00	12.00
Sequoyah	17.00	9.00	9.00	10.00	16.00	15.00	9.0
Stephens	17.00	8.00	9.00	11.00	15.00	14.00	12.00
Texas	17.00	9.00	8.00	11.00	15.00	14.00	11.00
Tillman	19.00	10.00	9.00	8.00	15.00	9.00	8.00
Tulsa	12.00	8.00	10.00	8.00	13.00	12.00	9.00
Wagoner	12.00	8.00	10.00	8.00	13.00	12.00	9.00
Washing	12.00	8.00	10.00	8.00	13.00	12.00	9.00
Washita	18.00	11.00	10.00	8.00	16.00	12.00	8.00
Woods	14.00	11.00	11.00	13.00	16.00	14.00	13.00
Woodward	14.00	11.00	11.00	13.00	16.00	14.00	13.00

+	Oct	Nov	Dec	Jan	Feb
Adair	6.00	8.00	15.00	15.00	8.00
Alfalfa	7.00	11.00	13.00	16.00	17.00
Atoka	5.00	12.00	16.00	12.00	9.00
Beaver	11.00	9.00	21.00	20.00	14.00
Beckham	3.00	12.00	18.00	18.00	17.00
Blaine	3.00	12.00	18.00	18.00	17.00
Bryan	5.00	12.00	16.00	12.00	9.00
Caddo	5.00	12.00	19.00	16.00	15.00
Canadian	5.00	11.00	17.00	18.00	17.00
Carter	5.00	12.00	16.00	12.00	9.00
Cherokee	6.00	8.00	15.00	15.00	8.00
Choctaw	2.00	10.00	10.00	11.00	10.00
Cimarron	11.00	9.00	21.00	20.00	14.00
Clevelan	5.00	11.00	17.00	18.00	17.00
Coal	5.00	12.00	16.00	12.00	9.00
Comanche	5.00	12.00	19.00	16.00	15.00
Cotton	5.00	12.00	19.00	16.00	15.00
Craig	6.00	12.00	15.00	15.00	15.00
Creek	5.00	11.00	17.00	18.00	17.00
Custer	3.00	12.00	18.00	18.00	17.00
Delaware	6.00	12.00	15.00	15.00	15.00
Dewey	3.00	12.00	18.00	18.00	17.00
Ellis	11.00	9.00	21.00	20.00	14.00
Garfield	7.00	11.00	13.00	16.00	17.00
Garvin	5.00	12.00	16.00	12.00	9.00
Grady	5.00	11.00	17.00	18.00	17.00
Grant	7.00	11.00	13.00	16.00	17.00
Greer	5.00	12.00	19.00	16.00	15.00
Harmon	5.00	12.00	19.00	16.00	15.00
Harper	11.00	9.00	21.00	20.00	14.00
Haskell	6.00	8.00	15.00	15.00	8.00
Hughes	6.00	8.00	15.00	15.00	8.00
Jackson	5.00	12.00	19.00	16.00	15.00
Jeffers	5.00	12.00	16.00	12.00	9.00
Johnston	5.00	12.00	16.00	12.00	9.00
Kay	7.00	11.00	13.00	16.00	17.00
Kingfish	5.00	11.00	17.00	18.00	17.00
Kiowa	5.00	12.00	19.00	16.00	15.00
LeFlore	2.00	10.00	10.00	11.00	10.00
Lincoln	5.00	11.00	17.00	18.00	17.00
Logan	5.00	11.00	17.00	18.00	17.00
Love	5.00	12.00	16.00	12.00	9.00
Major	7.00	11.00	13.00	16.00	17.00
Marshall	5.00	12.00	16.00	12.00	9.00
Mayes	6.00	12.00	15.00	15.00	15.00
McClain	5.00	11.00	17.00	18.00	17.00
McCurt	2.00	10.00	10.00	11.00	10.00
McIntosh	6.00	8.00	15.00	15.00	8.00
Murray	5.00	12.00	16.00	12.00	9.00
Muskogee	6.00	8.00	15.00	15.00	8.00
Noble	7.00	11.00	13.00	16.00	17.00
Nowata	6.00	12.00	15.00	15.00	15.00
Okfuskee	5.00	11.00	17.00	18.00	17.00
Oklahoma	5.00	11.00	17.00	18.00	17.00
Okmulgee	6.00	8.00	15.00	15.00	8.00
Osage	6.00	12.00	15.00	15.00	15.00

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Ottawa          6.00   12.00   15.00   15.00   15.00
Pawnee          6.00   12.00   15.00   15.00   15.00
Payne           5.00   11.00   17.00   18.00   17.00
Pittsbur        6.00    8.00   15.00   15.00    8.00
Pontotoc        5.00   12.00   16.00   12.00    9.00
Pottawat        5.00   11.00   17.00   18.00   17.00
RogerMil        3.00   12.00   18.00   18.00   17.00
Rogers          6.00   12.00   15.00   15.00   15.00
Seminole        5.00   11.00   17.00   18.00   17.00
Sequoyah        6.00    8.00   15.00   15.00    8.00
Stephens        5.00   12.00   16.00   12.00    9.00
Texas          11.00    9.00   21.00   20.00   14.00
Tillman         5.00   12.00   19.00   16.00   15.00
Tulsa           6.00   12.00   15.00   15.00   15.00
Wagoner         6.00   12.00   15.00   15.00   15.00
Washing         6.00   12.00   15.00   15.00   15.00
Washita         3.00   12.00   18.00   18.00   17.00
Woods           7.00   11.00   13.00   16.00   17.00
Woodward        7.00   11.00   13.00   16.00   17.00
;

***********************************************************************************
** 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)                                            *
**                                                                                *
** The Daily capacity of mowing harvest unit was recalculated based on the Table 7 *
** in Thorsell's thesis using a MACHSEL program (see Table C-5 in Appendix C)     *
** So, the esimated average capacities are 122 tons per day for a mowing harvest  *
** unit and 355 tons per day for a raking-baling-stacking harvest unit.           *
**                                                                                *
** Because duration of daylight time is different in each month, daily capacity   *
** was adjusted by month. March was assumed to be a base month to adjust.         *
** Adjust coefficients was calculated by proportion of duration of daylight in each*
** based on duration of daylight of March(12 hours).                              *
** Jan  Feb  Mar  Apr  May  Jun  Jul  Aug  Sep  Oct  Nov  Dec                     *
** 0.83 0.91 1.00 1.10 1.18 1.21 1.19 1.12 1.03 0.94 0.85 0.81                    *
** So, daily capacity of mowing harvest unit in April was computed by:            *
** April=122*1.10=134 tons per day with one mower                                 *
***********************************************************************************

PARAMETERS DCAMHU(M)"Daily Capacity of a Mowing Harvest Unit in tons by Month"
/Mar 122
 Apr 134
 May 143
 Jun 148
 Jul 146
 Aug 137
 Sep 126
 Oct 114
 Nov 104
 Dec  99
 Jan 102
 Feb 111 /;

PARAMETERS DCABHU(M)"Daily Capacity of a Baling Harvest Unit in tons by Month"
/Mar 355
 Apr 389
 May 417
 Jun 431
 Jul 424
 Aug 399
 Sep 366
 Oct 333
 Nov 303
 Dec 288
 Jan 296
 Feb 322 /;
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********************************************************************************
** Based upon the method developd by Thorsell(2004) and using a MACHSEL program    *
** the annual cost of using a mowing harvest unit and a raking-baling-stacking     *
** harvest unit were estimated (see Table C-2 and C-3 in Appendix C).              *
** Cost of a mowing harvest unit: $58,424                                          *
** Cost of a raking-baling-stacking harvest unit: $470,236                         *
********************************************************************************

SCALAR OMEGAM "Cost of a Harvest Unit for Mowing in $ per Unit" /58424/;
SCALAR OMEGAB "Cost of a Harvest Unit for Baling in $ per Unit" /470236/;
SCALAR ACDM "Adjusted coefficient for dry matter" /1.0/;

PARAMETER CAPHUM(I,M) "Monthly capacity of harvest unit FOR MOWING in tons";
        CAPHUM(I,M) = FWD(I,M)*DCAMHU(M);

PARAMETER CAPHUB(I,M) "Monthly capacity of harvest FOR BALING unit in tons";
        CAPHUB(I,M) = BWD(I,M)*DCABHU(M);

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                Total number of harvest unit
  HUM               Number of Harvest Units FOR MOWING
  HUB               Number of Harvest Units FOR BALING
  XHUM(I,M)         Harvest Unit FOR MOWING in county i in month m
  XHUB(I,M)         Harvest Unit FOR BALING in county i in month m
  BETA(J,S)         Zero-one variable for plant size s at j

POSITIVE VARIABLES Q, A, XT, XP, XSI, XSIP, XSIN, XSJ,X, XHUM, XHUB;
BINARY VARIABLE BETA;
INTEGER VARIABLE HUM,HUB ;

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
  HUBLM(M)          Harvest Units balance for Mowing
  HUBLB(M)          Harvest Units balance for Baling
  TTONSHMM(I,M)     Capacity of harvest unit for Mowing in tons by county and month
  TTONSHMB(I,M)     Capacity of harvest unit for Baling in tons by county and month
  TTONSHB(I,M)      Capacity of Harvest unit balance
  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 ;

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))
               -OMEGAM*HUM-OMEGAB*HUB}*PVAF ;

*LANDCON(I,K)$(ORD(K) NE 1)..       SUM(KF$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;

HUBLM(M)..                         SUM(I, XHUM(I,M))- HUM =L= 0;

HUBLB(M)..                         SUM(I, XHUB(I,M))- HUB =L= 0;

TTONSHMM(I,M)..                    SUM(KF, X(I,KF,M)) - (XHUM(I,M)*CAPHUM(I,M)) =L= 0;

TTONSHMB(I,M)..                    SUM(KF, X(I,KF,M)) - (XHUB(I,M)*CAPHUB(I,M)) =L= 0;

TTONSHB(I,M)..                    (XHUM(I,M)*CAPHUM(I,M))-(XHUB(I,M)*CAPHUB(I,M))=E= 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;
```

```
HUM.UP=200;

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,XHUM.L, XHUB.L;

***RESULTS SUMMARY***
PARAMETER TXHUM Total harvest unit for mowing activity by month;
  TXHUM(M) = SUM(I, XHUM.L(I,M));

PARAMETER TXHUB Total harvest unit for baling activity by month;
  TXHUB(M) = SUM(I, XHUB.L(I,M));

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 IMBIOHAR Total biomass harvested by county;
  IMBIOHAR(I,M) =  SUM(KF, X.L(I,KF,M));

PARAMETER AKBIOHAR Total biomass harvested acres by county;
  AKBIOHAR(I,K) = SUM(M, SUM(KF$KKF(K,KF), A.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, IMBIOHAR,AKBIOHAR, MBIOSTO, MBIOSTON, MBIOSHIP, BIOSHIP, BIOSHIPIJ,
PLTR, MBIOSTJ,
        PROPCAPM, PROPCAP,TXHUM,TXHUB;

***ENERGY BALANCE CALCULATIONS***

PARAMETER NITEN Energy in nitrogen fertilizer in Btu;
  NITEN = NBTU*SUM([I,KF,M], A.L(I,KF,M)*NIT(KF));

PARAMETER TPTEN Energy expended during biomass shipment in Btu;
 TPTEN = (GPM/17)*DBTU*SUM([I,J,S,K,M], XT.L(I,J,S,K,M)*2*DELTA(I,J));

PARAMETER FLDEN(I,KF) Energy spent per acre of each of the cropping activities;
 FLDEN(I,KF)$(ORD(KF) EQ 22) = SUM(M, A.L(I,KF,M))*SUM(FA$TFA
                               ("Harvest",FA), FLDIES(FA))*DBTU
                               + SUM(M, A.L(I,KF,M))*SUM(FA$TFA
                               ("Estab",FA), FLDIES(FA))*DBTU/T;

 FLDEN(I,KF)$(ORD(KF) NE 22) = SUM(M, A.L(I,KF,M))*SUM(FA$TFA
                               ("Harvest",FA), FLDIES(FA))*DBTU;

PARAMETER TFLDEN Total energy spent in field activities;
 TFLDEN = SUM([I,KF], FLDEN(I,KF));

**The following equation computes energy spent in grinding**
PARAMETER GRDEN Diesel energy spent in grinding the biomass in Btu;
 GRDEN = DBTU*GRDIES*SUM([J,S,M], Q.L(J,S,"Ethanol",M))/IOE;

PARAMETER TOTEN Totatl energy spent in Btu;
 TOTEN = NITEN + TPTEN + TFLDEN + GRDEN;

PARAMETER ENYLD Total energy yield from the produced ethanol (Btu);
 ENYLD = SUM([J,S,M], Q.L(J,S,"Ethanol",M)*EBTU);

PARAMETER NETEN Net energy in Btu;
 NETEN = ENYLD - TOTEN;

DISPLAY FLDIES, NITEN, TPTEN, FLDEN, TFLDEN, GRDEN, TOTEN, ENYLD, NETEN;

************************************************************
*Partitioning total costs into its components             *
************************************************************

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;
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  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 HRVUNTSM   Harvest Units FOR MOWING to be purchased;
        HRVUNTSM = HUM.L;

PARAMETER HRVUNTSB   Harvest Units FOR BALING to be purchased;
        HRVUNTSB = HUB.L;


PARAMETER HARVCO Total Cost of Harvesting using Harvest Units;
         HARVCO = OMEGAM*HUM.L+OMEGAB*HUB.L;

PARAMETER TPCOST Total Biomass Purchase Cost in $ per ton;
         TPCOST = 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, HRVUNTSM,HRVUNTSB, HARVCO, TPCOST;

SCALAR IT;
FOR(IT = 1 TO 0,
   RHO(E) = RHO(E) - 0.001;
   SOLVE ETHANOL MAXIMIZING NPW USING MIP;


   DISPLAY RHO, BETA.L, Q.L, XP.L;

   TOTLAND(K,M) = SUM(KF$KKF(K,KF), SUM(I, A.L(I,KF,M)));
   TLANDM(M) = SUM([I,KF], A.L(I,KF,M));
   TLANDK(K) = SUM(KF$KKF(K,KF), SUM([I,M], A.L(I,KF,M)));
   TLANDRK(R,K) = SUM(I$IR(I,R), SUM(KF$KKF(K,KF), SUM(M, A.L(I,KF,M))));
   TLANDR(R) = SUM(K, TLANDRK(R,K));

   TOTBIO = SUM([I,KF,M], X.L(I,KF,M));
   MBIOHAR(M) = SUM([I,KF], X.L(I,KF,M));
   IKBIOHAR(I,K) = SUM(M, SUM(KF$KKF(K,KF), X.L(I,KF,M)));
   MBIOSTO(M) = SUM([I,K], XSI.L(I,K,M));
   MBIOSTON(M) = SUM([I,K], XSIP.L(I,K,M));
   MBIOSHIP(M) = SUM([I,J,S,K], XT.L(I,J,S,K,M));
   BIOSHIP(K,M) = SUM([I,J,S], XT.L(I,J,S,K,M));
   BIOSHIPIJ(I,J) = SUM([S,K,M], XT.L(I,J,S,K,M));

   PLTR(J,R)$JR(J,R) = SUM(S, BETA.L(J,S));
   MBIOSTJ(M) = SUM([J,S,K], XSJ.L(J,S,K,M));
   PROPCAPM(J,S,M) = 100*Q.L(J,S,"Ethanol",M)/CAPP(S);
   PROPCAP(J,S) = 100*SUM(M, Q.L(J,S,"Ethanol",M))/(12*CAPP(S));

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

***ENERGY BALANCE CALCULATIONS***

   NITEN = NBTU*SUM([I,KF,M], A.L(I,KF,M)*NIT(KF));
   TPTEN = (GPM/17)*DBTU*SUM([I,J,S,K,M], XT.L(I,J,S,K,M)*2*DELTA(I,J));

   FLDEN(I,KF)$(ORD(KF) EQ 22) = SUM(M, A.L(I,KF,M))*SUM(FA$TFA
                               ("Harvest",FA), FLDIES(FA))*DBTU
                               + SUM(M, A.L(I,KF,M))*SUM(FA$TFA
                               ("Estab",FA), FLDIES(FA))*DBTU/T;
   FLDEN(I,KF)$(ORD(KF) NE 22) = SUM(M, A.L(I,KF,M))*SUM(FA$TFA
                               ("Harvest",FA), FLDIES(FA))*DBTU;
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   TFLDEN = SUM([I,KF], FLDEN(I,KF));

**The following equation computes energy spent in grinding**
   GRDEN = DBTU*GRDIES*SUM([J,S,M], Q.L(J,S,"Ethanol",M))/IOE;

   TOTEN = NITEN + TPTEN + TFLDEN + GRDEN;

   ENYLD = SUM([J,S,M], Q.L(J,S,"Ethanol",M)*EBTU);

   NETEN = ENYLD - TOTEN;

   DISPLAY FLDIES, NITEN, TPTEN, FLDEN, TFLDEN, GRDEN, TOTEN, ENYLD, NETEN;

************************************************************
*Partitioning total costs into its components              *
************************************************************

  PRODCO = SUM([I,K,M], TPOC(K)*SUM(KF$KKF(K,KF), A.L(I,KF,M)));
  LDCO = SUM([I,K,M], POC(K,"Landrent")*SUM(KF$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)));
  ESMCO = PRODCO - LDCO;

  NITCO = SUM([I,KF,M], NCOST(KF)*A.L(I,KF,M));

  FLDCO = ESMCO + NITCO;

  TPTCO = SUM([I,J,S,K,M], TAU(I,J)*XT.L(I,J,S,K,M));

  STORCO = SUM([I,K,M], GAMMA(K)*XSIP.L(I,K,M));

  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));

  TFXDCO = SUM(FT, FXDCO(FT));

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

  DISPLAY ESMCO, NITCO, PRODCO;
  );
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VITA

Seonghuyk Hwang

Candidate for the Degree of

Doctor of Philosophy

Thesis: DAYS AVAILABLE FOR HARVESTING SWITCHGRASS AND THE COST TO DELIVER SWITCHGRASS TO A BIOREFINERY

Major Field: Agricultural Economics

Biographical:

Personal Data**:** Born in Seoul, Korea, on July 08, 1971, the son of father Dae-Ho Hwang and mother Bok-Soon Ko.

Education: Graduated from Seong-Nam High School, Seoul, Korea, in February 1990; received a Bachelor of Science degree in Industrial Economics from Chung-Ang University, Seoul, Korea, in February 1997; received a Master of Science in Industrial Economics from Chung-Ang University, Seoul, Korea, in June 1999. Completed the requirements for the Doctor of Philosophy degree in Agricultural Economics at Oklahoma State University in July 2007.

Experience: Graduate Research Assistant, Department of Agricultural Economics, Oklahoma State University, Stillwater, Oklahoma, August 2002 to July 2007; Temporary Researcher, Korean Food Research Institute, Seong-Nam, Korea, February 1999 to July 2000; Graduate Teaching Assistant, Department of Industrial Economics, Chung-Ang University, March 1997 to February 1999.

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

Name: Seonghuyk Hwang Date of Degree: July, 2007

Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of Study: DAYS AVAILABLE FOR HARVESTING SWITCHGRASS AND THE COST TO DELIVER SWITCHGRASS TO A BIOREFINERY

Pages in Study: 201 Candidate for the Degree of Doctor of Philosophy

Major Field: Agricultural Economics

Scope and Method of Study: The purpose of this study was to estimate the number of suitable field workdays per month in which switchgrass can be harvested in Oklahoma at different probability levels. This study also sought to determine the effect of the number of workdays on the cost to deliver a flow of feedstock to a biorefinery. A soil moisture balance model, drying model of cut grasses, and empirical CDF were used to determine the number of field workdays for mowing and baling operations at different probability levels. A mixed integer mathematical programming model was used to determine the optimal biorefinery location, the quantity of biomass feedstock, monthly harvest and storage quantities, optimal number of mowing and raking-baling-stacking harvest machines, and the cost to deliver feedstock to a biorefinery.

Findings and Conclusions: Harvest cost depends on the number of required harvest machines, which are constrained by the number of field workdays during the harvest window. The number of workdays for mowing and baling varies across months and regions. At the 95 percent probability level, October is the month with the least amount of time for baling switchgrass (average nine days). The southeast region of Oklahoma, which on average receives the most precipitation, has the least number of available workdays (174 mowing days and 115 baling days for a year). This information was used to determine the investment required in harvest machines to provide switchgrass to a biorefinery. The optimal number of harvest units was 48 for mowing and 20 for raking-baling-stacking, which requires an average investment in harvest machines of $11.2 million for a 2,000 dry tons per day biorefinery. The estimated cost to deliver feedstock was $49.7 per ton and harvest cost was $17.0. Under the assumption of only three days available in each month as workdays, the estimated cost to deliver feedstock and harvest cost were $141 and $109, respectively. Ignoring or using an incorrect estimate of the number of workdays would result in incorrect feedstock cost estimates and an incorrect estimate of the investment required in harvest machinery.

ADVISOR'S APPROVAL: Dr. Francis Epplin ____________________________________