Days Available for Harvesting Lignocellulosic Biomass

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Abstract

A reasonably precise estimate of the number of harvest days is necessary to determine the investment in harvest machines required to support a lignocellulosic biorefinery. This study was undertaken to determine probability distributions for the number of suitable field work days per month for harvesting perennial grasses such as switchgrass.

Introduction

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. 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 is a function of protein content that depends critically upon the timing of harvest. However, for a biorefinery that uses a gasification-fermentation process, the key component of the LCB is the mined atmospheric carbon contained in the lignin and cellulose. Hence, the window for harvest is expected to be lengthy. Thorsell et al. found that if a biorefinery could use a variety of LCB feedstocks 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.

Mapemba and Epplin, and Tembo, Epplin, and Huhnke 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 a nine month harvest season. However, they 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).

To determine a more precise estimate of the number of harvest machines required to harvest and provide LCB to a biorefinery, and a more precise estimate of harvest costs, a more precise estimate 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. Therefore, the objective of the research is to determine probability distributions for the number of suitable field work days per month for harvesting crop residues and perennial grasses such as switchgrass in Oklahoma.

Procedures

Harvest of perennial grasses requires a cutting or mowing operation and a gathering or baling operation. Depending upon the material to be harvested and type of cutting system (mower, windrower) intermediate steps of raking and/or tedding may be required. Probability distributions are required for the number of mowing days per month and separate probability distributions for the number days suitable for baling per month. Weather requirements for baling are more stringent than requirements for mowing.

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

To determine if a day will be classified as a work or non-work day, values for several variables are required, including weather condition of day, soil tractability, and moisture content of perennial grasses after cutting. Rainy days (rainfall > 0mm) and snowy days (snowfall > 0mm) are defined as non-work days.

A soil is considered tractable if a tractor or other farm machine can move on that soil and satisfactorily perform the function of the machine, without causing significant damage to the soil (Hassan and Broughton; Babeir, Colvin and Marley). This ability depends on the soil moisture content. High moisture content increases 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). Field operations require decisions as to when the soil is tractable or non-tractable (Rounsevell and Jones).

Tractability criteria can be defined and used to differentiate between a tractable and non-tractable soil. 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 or not (Babeir, Colvin and Marley; Rotz and Harrigan).

The soil moisture criterion is expressed as

(1) $$\begin{cases} FM < CT \rightarrow \text{ Working day} \\ FM \geq CT \rightarrow \text{ Non-workable day} \end{cases}$$

where FM is the ratio of allowable moisture in the top soil layer (surface to 15 cm) and CT is defined as the coefficient of tractability.

FM can be defined by

(2) $$FM = \frac{\text{Actual available moisture of top layer (mm)}}{\text{Maximum available moisture of top layer (mm)}}$$

If the soil moisture (FM) on a particular day is above the established criterion (CT), that day is classified as a non-work day and vice versa.

The maximum available moisture of the top soil layer differs across soil types. The coefficient of tractability is the ratio of allowable moisture in the top soil layer to that at field capacity. Rotz and Harrigan recommend using 1.01 for clay, 1.02 for loam, and 1.04 for sandy soil.

The degree of dryness, that is, moisture content of perennial grasses on the ground must be considered prior to baling (Hadders and Olsson). Baling material with moisture content in excess of 20 percent may result in molding and heating and in some cases spontaneous combustion. Baling at lower than 15 percent moisture will result in greater harvesting losses because leaf loss increases as moisture decreases. Typical moisture content of perennial grasses for baling is 15%. Therefore, when moisture content of cut material is 15%, or less, that day is classified as a baling day. To decrease moisture content of cut material, favorable weather conditions are needed; no rain, low air humidity, and high solar radiation. Figure 1 includes a summary of factors that affect mowing and baling decisions.

Soil Water Balance Model

To estimate the number of available mowing and baling days, information regarding daily fluctuation of soil moisture content is required. A field water balance model can be used to estimate soil moisture content. The soil moisture content in a soil profile at the current time is represented by

$$SW_t = SW_{t-1} + P - R - ET - D \tag{3}$$

where SW_t is the soil water content in the current time, SW_{t-1} is the antecedent soil water content, P is the precipitation, R is surface runoff, ET is evapotranspiration, and D is drainage or deep percolation below the soil profile.

For nonirrigated soils, precipitation is the only source of water to the soil profile. The total amount and the intensity of precipitation influence the amount of water entering the soil. Because movement of water into the soil profile takes time, more water will be absorbed form 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 moisture status of the soil (Bargen et al., p.4).

Surface runoff is that 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., p.68). Surface runoff can be estimated using the SCS Runoff Curve Number (CN) method developed by U.S. Soil Conservation Service (SCS) in 1972. The SCS runoff equation is

$$R = \frac{(P - 0.2S)^2}{(P + 0.8S)} \quad \text{for} \quad P \geq 0.2S \tag{4}$$

where R is a 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 occur, 0.2S is the initial abstraction from the rainfall (Schwab et al.; SCS). S is given by:

$$S = \frac{25400}{CN} - 254 \tag{5}$$

Runoff curve number (CN), which is reflected on the characteristics of soil, vegetative-cover, and hydrological condition, was provided by SCS.

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 combined and referred to as evapotranspiration (Schwab et al., pp 53-4).

However; since evaporation and transpiration occurs 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., p. 3).

Thus, actual evapotranspiration varies with crop type. Actual evapotranspiration is given by

$$ET = K_c ET_o \tag{6}$$

where K_c is a crop coefficient and ET_o is a standardized reference or potential evapotranspiration in mm/day.

There are several methods for estimating standardized reference evapotranspiration, ET_o. Among these methods, Allen et al. recommend the Peman-Moneith method because it needs minimal calibrations for adjusting to local weather conditions. Thus, this study employed the FAO Penman-Monteith equation to estimate ET_o. The FAO Penman-Monteith (FAO-PM) equation is given below (Allen et al; Sutherland, Carlson, and Kizer).

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{C_n}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)} \tag{7}$$

where R_n is net radiation at the crop surface (MJ/m^2/day), G is a soil heat flux density at the soil surface (MJ/m^2/day), T is a mean daily air temperature at 2 m height (°C), u_2 is a mean daily wind speed at 2 m height (m/second), 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), γ is a psychrometric constant (kPa/°C), C_n is a numeration constant that changes with reference type and calculation time step, and C_d is a denominator constant that change s with reference type and calculation time step.

Drainage is the amount of water that passes below the root zone of crops. Dyer and Baier 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 place over one or more days. This effect may be 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 out of soil layer may be computed by

$$D_i = DRS\left[(P_i - R_i) - D_{r,i-1}\right] \geq 0 \tag{8}$$

where DRS is a drainage coefficient [0~1], P_i is the precipitation at i time, R_i is the surface runoff at i time, and $D_{r,i-1}$ is the depletion at i-1 time.

Drying of Cut Grasses Model

During the day cut grasses lose moisture by diffusion and evaporation into the atmosphere under favorable weather conditions such as sunshine. On the other hand, moisture content of cut grasses increases during the night because of no sunlight, low temperature, and high humidity. Cut biomass must be left on the ground until the moisture content decreases below the threshold level (e.g. 15%) and then the material can be safely baled. Therefore, a drying and rewetting model is necessary to estimate the number of baling days.

This study employed the drying model developed by Rotz and Chen to calculate the field drying rate of cut biomass. Rotz and Chen originally developed their model to find the field drying rate for alfalfa. Later they applied the model to determine field drying of cut grasses (Rotz and Coiner). The drying model is

$$DR = \frac{SI + 43.8(VPD)}{2767 + 61.4(SM) + 1.68(SD)(1.82 - 0.83(DAY))} \tag{9}$$

where DR is the drying rate, SI is the solar insolation (W/m^2), VPD is the vapor pressure deficit (kPa), SM is the soil moisture content (%), SD is the swath density (g/m^2), and DAY is 1 for day of cutting and 0 otherwise.

The change in moisture content of the cut biomass across each period of the day is described as an exponential function

(10) $$M = M_o \exp[-DR(T)]$$

where M is the moisture content (dry basis) at the end of time T, M_o is the moisture content (dry basis) at the beginning of time T, and T is the length of drying period (hours).

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). Dew was assumed to be absorbed into cut grass following an exponential function of the moisture ratio, swath density and time.

(11) $$M_f = M_e + (M_i - M_e)\exp(-(T)(WR)/(SD))$$

where M_f is the moisture content (dry basis) at the end of night (i.e. at sunrise), M_e is the equilibrium moisture content (dry basis) in the night environment, M_i is the moisture content (dry basis) at the beginning of night (i.e. at sunset), T is the length of night period (hours), and WR is the dew moisture absorption rate of cut grass = 4.0 g/m^2/hour.

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

(12) $$M_e = e^{-2.5(1-RH)}\left(0.4 + 3.6e^{-0.2(WIND)}\right)$$

Where RH is the average nighttime relative humidity (fraction) and WIND is the average nighttime wind speed at 2m (m/second).

A form of equation (9) may be used to characterize rewetting from rain absorption. In this case, the equilibrium moisture content was fixed at a value of four. 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 used (Rotz).

$$M_r = 4.0 + (M_o - 4.0)\exp(-WR(RF)/SD) \tag{13}$$

where M_r is the moisture content following rain, WR is the moisture absorption rate of cut grass (= 150 g/m^2 / mm), and RF is the rainfall (mm).

Probability Distributions

To determine the probability distribution of the number of suitable mowing and baling days, empirical cumulative probability distributions functions (Empirical CDF) were constructed from the sequences of “working day” and “non-working day”. First, for each time period (e.g. month) in each year for which historical data are available, estimates of mowing and baling days can be summed. For example, the estimated quantity of mowing days in July are 25, 23, 27, and 20 based on weather data from 1994, 1995, 1996, and 1997, respectively. Second, the observations were arranged from smallest to largest. Finally, a discrete empirical CDF was constructed (Rosenberg et al.).

Data

Daily meteorological data were required to determine the soil moisture content of the top 15 cm (about 6 inches) of the soil profile. The following variables: daily rainfall (inch), maximum air temperature (°F), minimum air temperature (°F), daily average air temperature (°F), maximum relative humidity (%), minimum relative humidity (%), daily average relative humidity (%), daily total solar radiation (MJ/m^2), maximum dew point temperature (°F), minimum dew point temperature (°F), daily average station pressure (kPa), daily average wind speed at 2m (m/second), daily average wind speed at 10m (m/second), and standard deviation of wind speed at 10m (m/s) were used. These data (from January 1, 1994 to May 31, 2006) were obtained from the Oklahoma Mesonet. The Oklahoma Mesonet is a system designed to measure the environment at the size and duration of mesoscale weather events. 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 10-meter-tall tower and the observations are transmitted to a central facility every 5 minutes, 24 hours per day year-round (Figure 2)[1]. The Oklahoma Mesonet produces daily data from the data recorded every 5 minutes (Oklahoma Mesonet). During the 12 years and 5 months for which data were collected, each site produced more than 1.3 million 5-minute observations.

For the drying model of cut grasses, hourly meteorological data were needed. Oklahoma Mesonet 5-minute raw observations were obtained directly from Oklahoma Mesonet (Reader) and used to generate hourly observations. In other words the 1.3 million 5-minute observations were converted into nearly 109,000 hourly observations.

Since the biomass material is assumed to be permitted to dry after cutting and prior to windrowing, the swath density can be assumed to be the same as dry matter yield. The swath density used in this study of 1,587 g/m^2 was based upon the assumed yield of switchgrass in the region (Taliaferro).

Mesonet data from nine Oklahoma counties were used in combination with the models to determine the number of mowing and baling days. The selected nine counties are shaded in Figure 3. One county was selected from each of Oklahoma's nine agricultural statistics districts.

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[1] Weather variables measured every 5 minutes are following as: 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.

Results

Empirical CDFs were computed for each month for each of the 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 work days for one year is not affected by other years. This assumption can be used because weather variables such as rainfall and evapotranspiration are independent from year to year.

Table 1 and Table 2 provide the estimated number of available mowing days and baling days, respectively, per month during which perennial grass harvest can occur at no less than 50%, 70%, 80%, 90%, and 95% probability levels. Figure 4 through 15 shows the probability for 95% chance of 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 not exceed 15%. However, in some months, (i.e. November, December, January, February, March) there are small differences between the number of mowing and baling days. After grasses mature, the moisture content declines, 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 9 out of 10 years. The 50% probability level is the mean observation over the years for which data were available. For example, for the month of June, there are 20.5 mowing days and 18 baling days at the 50% probability level in the Southwest region. Hence, the average number of days for mowing and baling over the time period for which Mesonet data were available was 20.5 and 18 days, respectively, in the Southwest region for the month of June. However, there are only 11 mowing days and 8 baling days at the 95% probability level (19 out of 20 years) in the Southwest region. In other words, at least 11 field working days for mowing perennial grasses are expected in the Southwest region at the 95% probability level in June. Likewise, at least 8 days for baling are expected in the region Southwest area at 95% probability level in June.

Findings and Limitations

A model was developed to estimate days available for mowing and baling operations for perennial grasses. Estimates were based upon Oklahoma historical weather data. Since baling requires that the cut biomass be no more than 15% moisture, days suitable for baling are less than days suitable for mowing. 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%). The information may be used to determine the investment required in harvest machines to provide lignocellulosic biomass to a biorefinery.

Several limitations should be noted. First, only 12 years and 5 months of Mesonet data were available. Clearly, when dealing with weather, especially weather in the Great Plains of the U.S., observations from a much longer time period of time would be preferred. Second, while the component equations of the models have been validated by other researchers, data were not available to validate the results within the region.

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Table1. The Number of Mowing Days for Perennial Grasses for Five Probability Levels from an Empirical CDF for Oklahoma, Based upon 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

Table2. The Number of Baling Days for Perennial Grasses for Five Probability Levels from an Empirical CDF for Oklahoma, Based upon 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
	50	21.5	17.5	18.5	14.0	14.5	18.0	21.0	22.5	19.0	15.5	19.5	20.0

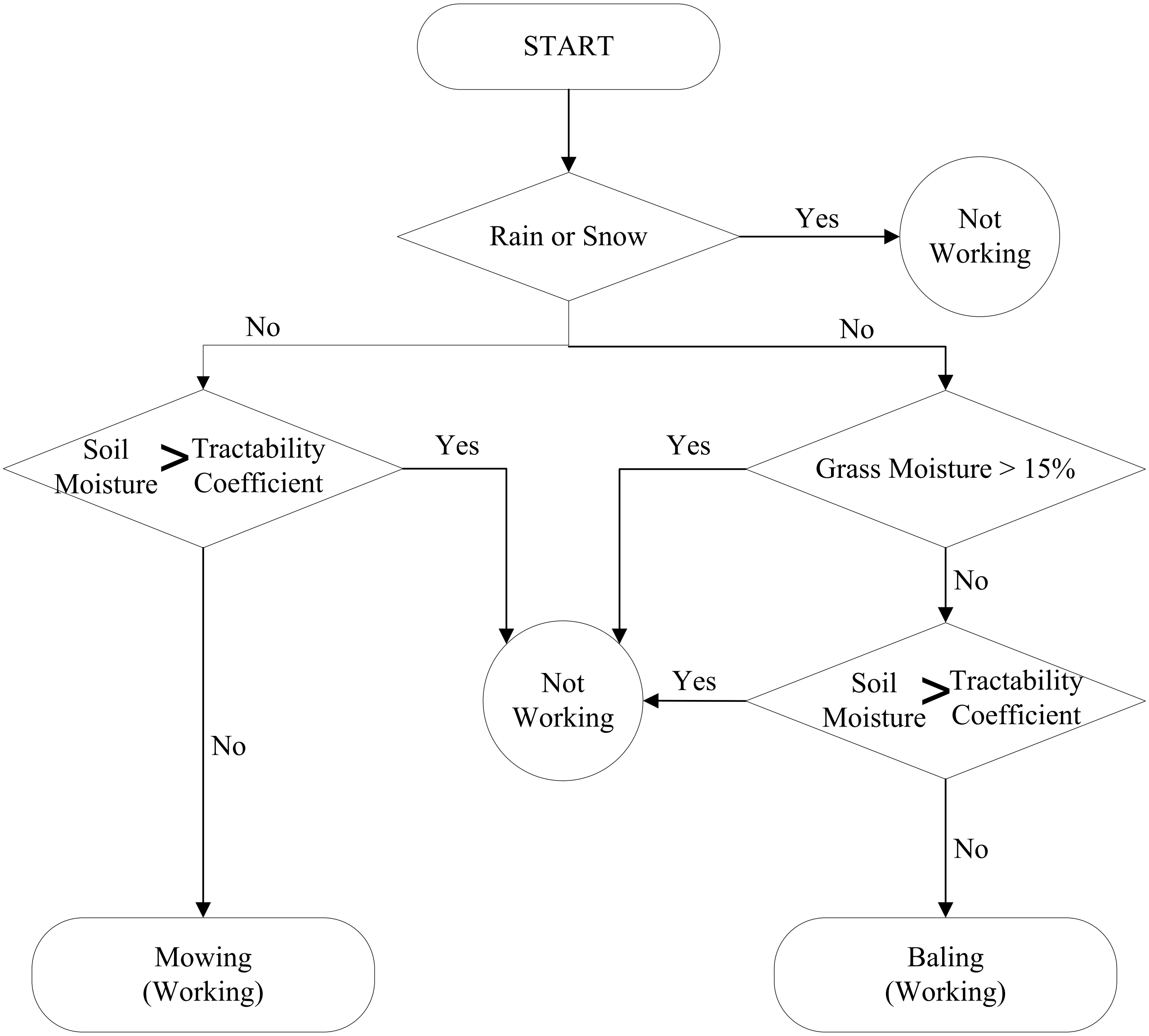

Figure 1. Flow chart of making decision of working day

Figure 2. Oklahoma Mesonet data collection station

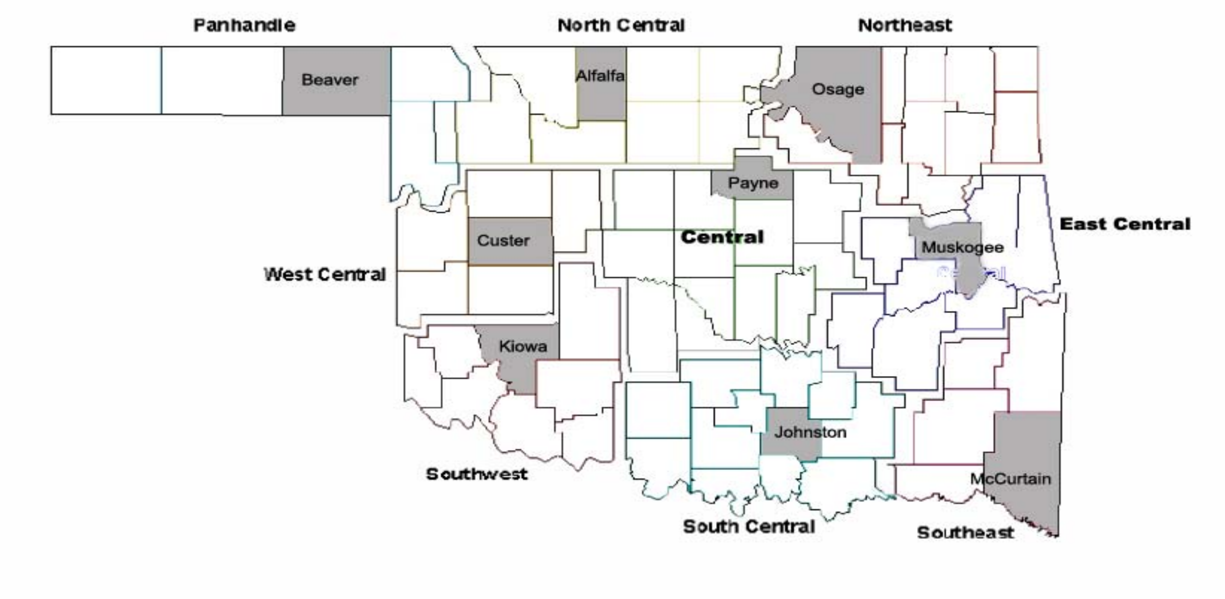

Figure 3. Map of Oklahoma showing the agricultural statistics regions. Data from stations located in shaded counties were used.

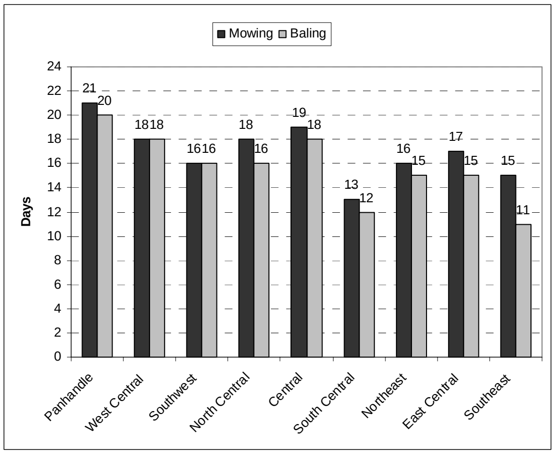

Figure 4. The Number of Mowing & Baling Days for January at 95% probability level

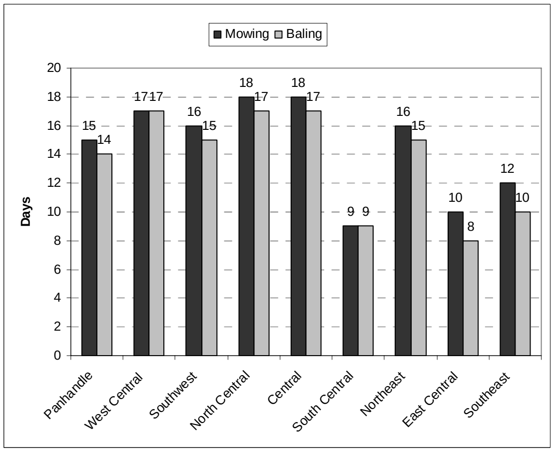

Figure 5. The Number of Mowing & Baling Days for February at 95% probability level

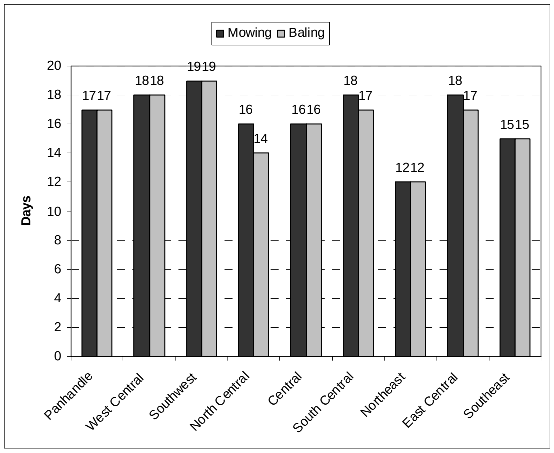

Figure 6. The Number of Mowing & Baling Days for March at 95% probability level

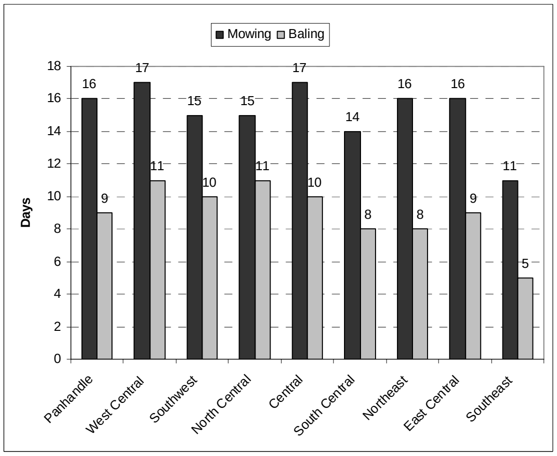

Figure 7. The Number of Mowing & Baling Days for April at 95% probability level

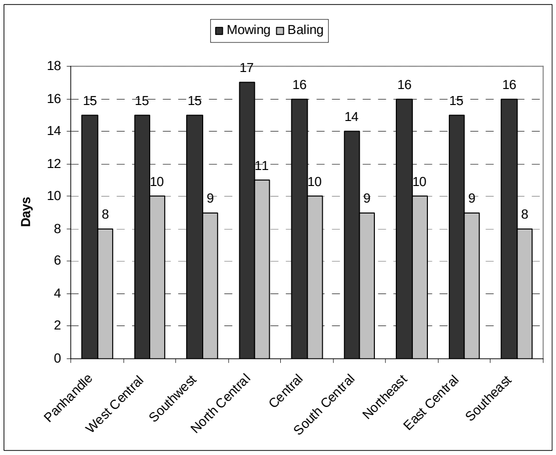

Figure 8. The Number of Mowing & Baling Days for May at 95% probability level

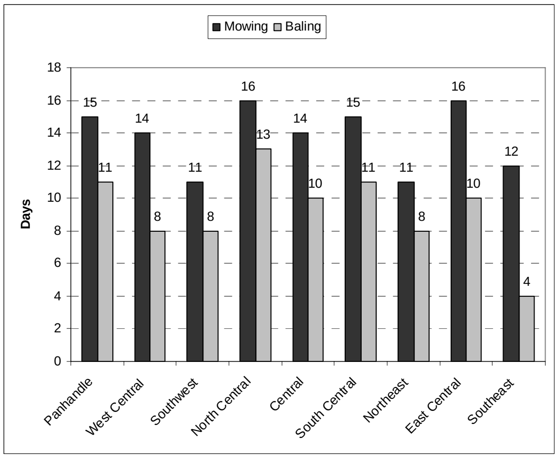

Figure 9. The Number of Mowing & Baling Days for June at 95% probability level

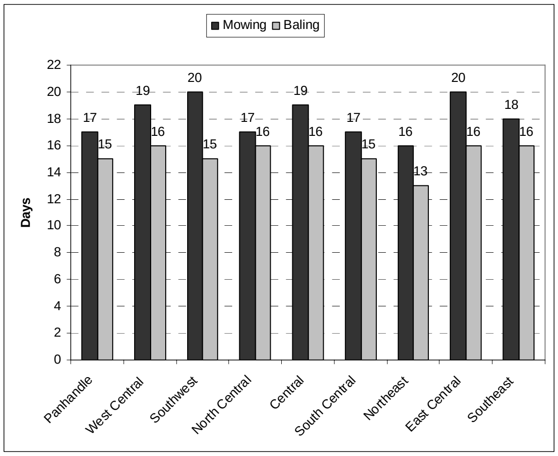

Figure 10. The Number of Mowing & Baling Days for July at 95% probability level

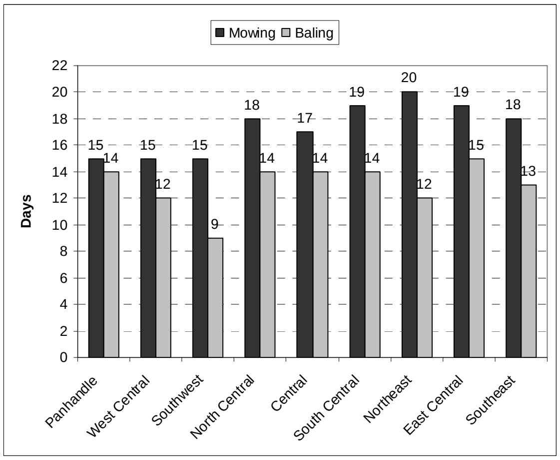

Figure 11. The Number of Mowing & Baling Days for August at 95% probability level

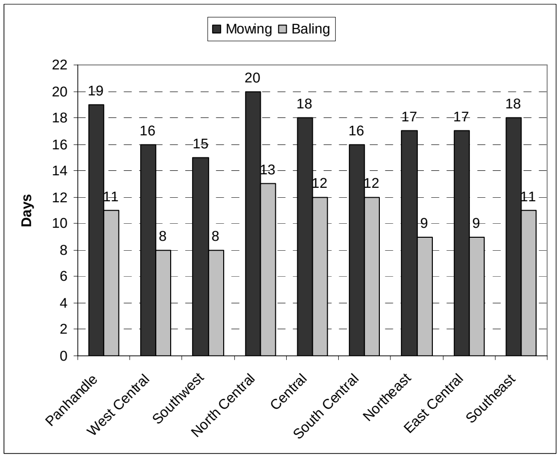

Figure 12. The Number of Mowing & Baling Days for September at 95% probability level

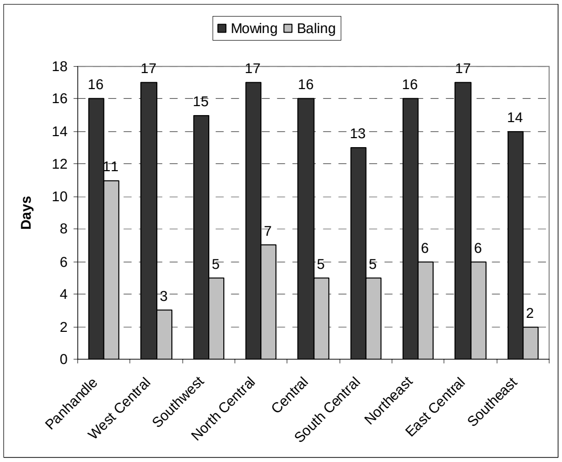

Figure 13. The Number of Mowing & Baling Days for October at 95% probability level

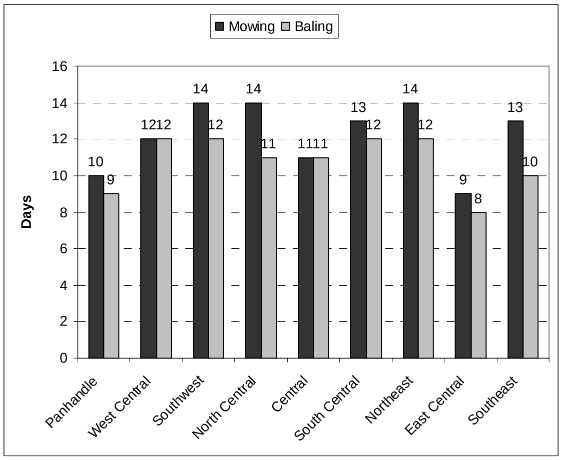

Figure 14. The Number of Mowing & Baling Days for November at 95% probability level

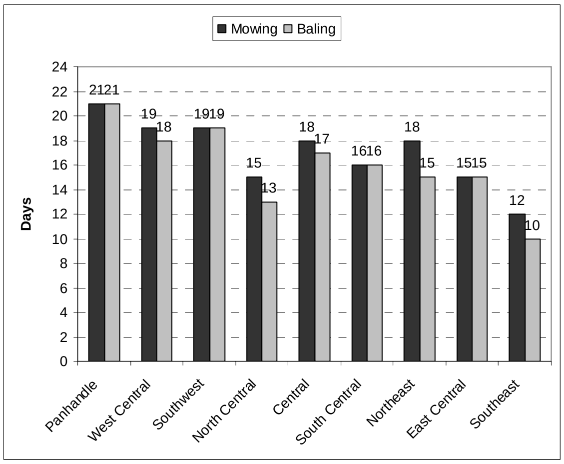

Figure 15. The Number of Mowing & Baling Days for December at 95% probability level