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AGRONOMY AND SOILS

Heat Unit Availability for Cotton Production in the Ogallala Aquifer Region of the United States

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ABSTRACT

Expansion of cotton (*Gossypium hirsutum* L.) production in the Ogallala Aquifer region of the United States can be attributed to early maturing cultivars, rising energy costs, and declining groundwater levels. The feasibility of growing cotton relative to the availability of heat units (HU) in this region has not been determined. In this study, a 30-yr (1971-2000), county-wide, daily maximum and minimum air temperatures database was developed to assess HU availability in the region. The time of planting used to initiate HU accumulation during the growing season was based on the estimated daily minimum soil temperature at planting depth. Linear regression models to estimate daily minimum soil temperature at planting depth using air temperature were developed for each of the climatic regions in the study area. The growing season was terminated with the first freeze or 15 October, whichever occurred first, and this was considered the harvest date. Total heat units (THU) based on the long-term annual averages and exceedance probability of 0.99 (every year) and 0.75 (3 out of 4 yr) were estimated and used to identify counties that are suitable for cotton production. Of the 131 counties evaluated, 110 received 1000 (°C) or more HU in 3 out of 4 yr. Based on heat unit availability, cotton is a suitable alternative crop for all counties in the Texas and Oklahoma panhandles and for the majority of counties in southwestern Kansas. Management uncertainties, such as irrigation efficiencies, soil types, fertilizer and pest management practices, and planting and harvest schedules, may require further consideration to determine the feasibility of cotton production in the region.

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Cotton is the most important textile fiber in the world. It accounts for more than 40% of the total world fiber production (MacDonald and Vollrath, 2005). Cotton is grown in more than 100 countries, and the United States ranked second in production behind China in 2004 (USDA-ERS, 2005). The annual revenue generated by cotton and its products in the United States accounts for about $40 billion. Cotton production in the United States has largely been located south of 37° N latitude in a region called the "Cotton Belt". In recent years, cotton production has expanded to include the Northern High Plains of Texas, the Oklahoma Panhandle, and parts of Kansas where corn (*Zea mays* L.) has traditionally been produced (Colaizzi et al., 2004). This expansion can be attributed to the development of early maturing cultivars (Duncan et al., 1993), rising energy costs, and declining water levels in the Ogallala Aquifer (Wheeler et al., 2004).

One option to reduce the use of groundwater from the Ogallala Aquifer is to plant more drought tolerant and economically viable crops. Crop water-use statistics for the Texas High Plains indicate that the cotton water requirement of 647 mm is less than other major crops grown in the region, such as corn (835 mm), sorghum (*Sorghum bicolor* (L.) Moench; 688 mm), and soybean (*Glycine max* (L.) Merr; 681 mm)(New and Dusek, 2005). After water, temperature is the second most yield-limiting factor in cotton production. Temperature can be a limiting factor in the Central and Northern High Plains of the Ogallala Aquifer region (Reddy et al., 1992a; Reddy et al., 1992b), since temperatures determine the length of the growing season. Furthermore, temperature is strongly related to cotton yield and quality (Reddy et al., 1999; Liakatas et al., 1998; Waddle, 1984).

Cotton development rates are related to air temperature during the growing season (Roussopoulos et al., 1998; Munro, 1987; McMahon and Low, 1972) and can be expressed as accumulated heat units (HU) or growing degree days. A HU is a measure of the amount of heat energy a plant accumulates each day during the growing season and has been used to describe the development of crops (Peng et al., 1989;

Wanjura and Supak, 1985). The HU for a given day (in °C) is calculated from the daily maximum and minimum air temperature as follows:

$$HU = (°C\ maximum + °C\ minimum) / 2 - T_t\ °C \quad \text{where } HU > 0.0 \qquad [1]$$

This concept of HU resulted from observations that plants do not grow below a threshold temperature (T_t). The T_t for a cotton plant is 15.6 °C. Crop growth and development of cotton are directly related to accumulated heat units when other environmental factors are not limiting (Peng et al., 1989). Total heat units (THU) accumulated during a growing season is calculated by the summing of all daily HU accumulated between planting and maturity dates. Cotton requires about 1444 HU from planting to maturity (Waddle, 1984). In recent years, farmers in the Texas Panhandle have shown that economically viable cotton can be grown with approximately one-third fewer heat units (Howell et al., 2004). A cotton plant can produce one open boll and four more bolls that are 85% mature with 1000 HU, and crop termination through defoliation at this stage of plant development results in a loss of about 1% of total expected yield but does not reduce the fiber quality (Wrona et al., 1996).

Planting and harvesting dates of cotton impacts crop growth, development, and yield (Davidonis et al., 2004; Unruh and Silvertooth, 1997). Early planting can expand the growing season and helps growers to avoid inclement weather near harvest and late-season pests (Steiner and Jacobsen, 1992); however, warmer soil conditions are required for seed germination and seedling emergence. Cotton seedlings are adversely affected when soil temperatures fall below 15.6 °C. In the Southern High Plains of Texas, Wanjura et al. (1967) showed that a minimum soil temperature between 15.6 and 20 °C was needed for supporting seedling emergence. If planted when soils are cooler than 12.8 °C, a cotton crop may suffer stand loss, seedling disease problems, and cold temperature stress, which reduce yield (Sansone et al., 2002).

Soil temperature at planting depth is influenced by air temperature because of the proximity of the seed zone to the atmosphere (Pregitzer et al., 2000). Therefore, changes in daily weather conditions can have a rapid and considerable influence on soil temperature at the seeding depth (Brown, 2000). Soil and air temperatures have a linear relationship, because the soil serves as an insulator for heat flowing between the earth's interior surface and the atmosphere. Numerous models have been developed to predict soil temperature by using air temperature (Paul et al., 2004; Brown, 2000; Kang et al., 2000; Gupta et al., 1981). Very large databases are required to develop models, when those models are to be extended widely to other locations (Gupta et al., 1984).

Interest is increasing among producers to grow cotton in the Ogallala Aquifer region; however, no formal study has been conducted to document the magnitude and frequency of THU available during the growing season for cotton. The primary objectives of this study were to develop linear statistical relationships between daily air and soil temperature data to determine an optimum time for cotton planting, and to quantify HU availability for cotton production in the Ogallala Aquifer region.

MATERIALS AND METHODS

Study area. Figure 1 illustrates the study area in the Ogallala Aquifer region of the United States. This study focused on counties located below 40 °N latitude, which includes all of the Southern High Plains, the Central High Plains, and a part of the Northern High Plains. Counties located north of the 40 °N latitude were not included in this study, because these areas probably had too short of a growing season. One hundred and thirty-one counties were included in the study area, totaling 41.32 M ha. This region has a semiarid to arid climate in the south that grades to a sub-humid climate in the north (McGuire et al., 2003). Annual precipitation in the area ranges from 366 mm in the western part to about 813 mm in the east. The major irrigated crops in the area include corn, winter wheat (*Triticum aestivum* L.), cotton, sorghum, soybean, and peanuts (*Arachis hypogaea* L.). Although the Southern High Plains is known to be acceptable for cotton production, it was included in this study for comparison.

Database development. Long-term weather data (1971-2000) from the National Climatic Data Center was used in this study (NCDC, 2002). This data set consisted of maximum and minimum air temperature from all weather stations in the Ogallala Aquifer region maintained by both the National Weather Service and local cooperating agencies. Based on the period, availability, and continuity of daily observations, a set of weather stations was selected. Daily values of maximum and minimum air temperatures were taken from a single station that had the most complete data in each county. Missing values were supplemented with data from neighboring stations within the same county. For counties with no weather stations, daily values of minimum and maximum air temperatures were calculated by averaging temperatures from surrounding counties. Data on daily minimum soil temperature was also collected for stations where it was available.

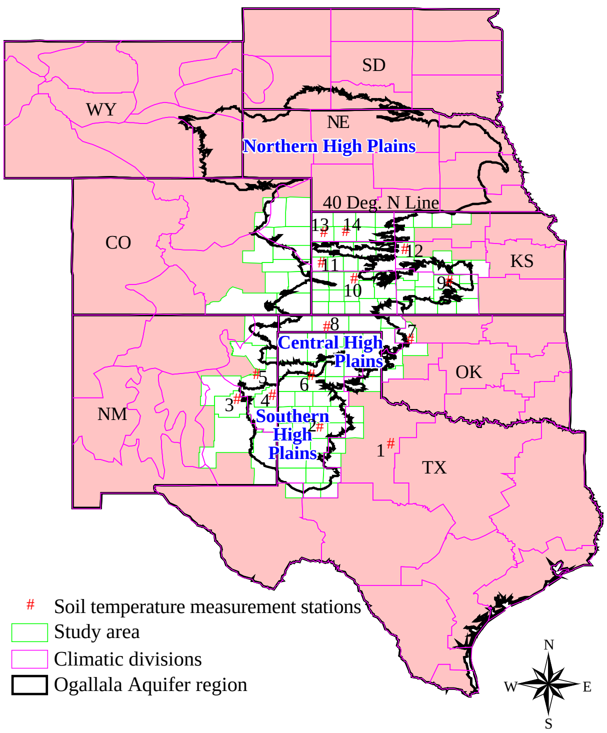

Figure 1. Climatic divisions and soil temperature monitoring stations in the study area of the Ogallala Aquifer.

Seasonal boundary conditions. County-wide planting dates for cotton each year were identified based on the predicted daily minimum soil temperatures. For predicting daily minimum soil temperature, the counties in the study area were grouped based on climatic regions developed and published by the NCDC (1991). Figure 1 illustrates the climatic regions and the location of the soil temperature monitoring stations in the study area. Each station location on the map is labeled with an identification number (ID) that corresponds to ID column in Table 1. The ID associated with each of the station locations on the map can be used to determine the station name in Table 1. Soil temperature data were measured at a depth of 102 mm for all stations except the Hutchison (204 mm) and Hays (51 mm) stations in Kansas. Soil and air temperature data from 1 April through 30 June were used to develop a statistical relationship over the typical planting season in the study area. Two sets of linear regression models were developed to predict daily minimum soil temperature. One model was based on the maximum air temperature and the other on the minimum air temperature for each climatic division (NCDC, 2002), as daily extreme air temperatures on the High Plains are highly variable. During the planting season, daily air temperature may vary from 0 °C in the early morning to 25 °C in the afternoon. Annual cotton planting dates for each county were identified when the county's estimated daily minimum soil temperature during the planting season was above or equal to a threshold value of 15.6 °C for both models.

The growing season was terminated on the first freeze (defined as –2.2 °C) or 15 October, whichever happened first, and this date was selected as the harvest date. Harvest date was designated 15 October because in the Southern High Plains the first freeze may not occur in October; however, producers typically apply harvest aid chemicals and begin harvest by the second week of October to avoid late season pests and fall precipitation that adversely affects fiber quality. In the Central and the Northern High Plains, freeze may occur during the last week of September, effectively terminating the crop regardless of the crop maturity.

Heat units. For each county, THU available for cotton between planting and harvest dates were calculated using Eq. [1], assuming no cotton cultivar response to base temperature. A computer program in FORTRAN was written to automatically calculate countywide HU accumulation during the growing season for all counties in the study area.

Climate variability. Climate variability from year to year impacts cotton yield as it affects total plant available heat energy during the growing season. A better understanding of the variability in THU over the long-term is important, because it aids in setting realistic yield goals and in planning appropriate management practices. Therefore, the THU was ranked in decreasing order for each county and the exceedance probability (P) was calculated as follows:

$$P = \frac{N}{(n+1)} \qquad [2]$$

where N is the rank of the annual estimated value and n is the total number of years (Davis et al., 2000; Haan et al., 1994). In this study, n is equal to 30. The exceedance probability for an event of a given magnitude is defined as the probability that an event of equal or greater magnitude will occur in any single year. The return period is the inverse of the *P*. For example, an event with a *P* of 0.25 occurs at least once in every 4 yr or a THU with a *P* of 0.75 occurs in 3 out of every 4 yr. Intuitively, producers want to know the lowest possible THU that they can expect in their county every year, i.e. $P = 0.99$. The next thing producers would want to know is, how much more yield they can expect, if they were to take some risk, because higher yield goals involve higher input (irrigation, fuel, fertilizer, etc) cost. Another scenario that may be of interest to producers would be a THU at $P = 0.75$ (3 out of every 4 yr) at which producers can expect a THU higher than the minimum.

A set of maps was generated using Arcview (version 3.3; ESRI Inc.; Redland, CA) to illustrate the spatial distribution of heat units over the study area. It included THU maps with exceedance probabilities of 0.99 (every year) and 0.75 (3 out of every 4 yr) in addition to a long-term average THU map.

RESULTS AND DISCUSSION

Seasonal boundary conditions. Two sets of linear regression models were developed to estimate daily minimum soil temperatures from corresponding air temperature data. Table 1 presents those

Table 1. Period of minimum daily soil temperature records and linear regression models developed to predict that value for 14 stations in climatic divisions of the study area.

ID	Station	Period of records	Regression model[z]	R^2
1	Haskell, TX	1982-1992	MinST = 2.78 + 0.55MaxAT	0.51
			MinST = 8.59 + 0.70MinAT	0.70
2	Lubbock, TX	1971-2000	MinST = 3.38 + 0.59MaxAT	0.47
			MinST = 9.78 + 0.76MinAT	0.67
3	Fort Sumner, NM	1982-2000	MinST = 8.78 + 0.43MaxAT	0.48
			MinST = 15.53 + 0.49MinAT	0.53
4	Clovis, NM	1970-1993	MinST = -4.38 + 0.66MaxAT	0.52
			MinST = 5.75 + 0.83MinAT	0.73
5	Tucumcari, NM	1976-2000	MinST = -0.46 + 0.65MaxAT	0.52
			MinST = 9.37 + 0.75MinAT	0.64
6	Bushland, TX	1977-2000	MinST = 2.40 + 0.49MaxAT	0.43
			MinST = 7.29 + 0.73MinAT	0.73
7	Mutual, OK	1980-2000	MinST = -1.01 + 0.70MaxAT	0.73
			MinST = 7.68 + 0.81MinAT	0.80
8	Goodwell, OK	1978-2000	MinST = 1.32 + 0.57MaxAT	0.60
			MinST = 8.78 + 0.75MinAT	0.73
9	Garden City, KS	1970-2000	MinST = 2.09 + 0.59MaxAT	0.60
			MinST = 9.21 + 0.83MinAT	0.78
10	Hutchison, KS	1970-2000	MinST = 1.11 + 0.63MaxAT	0.69
			MinST = 8.23 + 0.74MinAT	0.76
11	Tribune, KS	1970-2000	MinST = 0.69 + 0.55MaxAT	0.60
			MinST = 8.71 + 0.77MinAT	0.77
12	Hays, KS	1978-2000	MinST = -1.93 + 0.63MaxAT	0.64
			MinST = 4.63 + 0.86MinAT	0.84
13	Goodland, KS	1995-2000	MinST = 2.44 + 0.43MaxAT	0.42
			MinST = 7.44 + 0.73MinAT	0.71
14	Colby, KS	1994-2000	MinST = 2.84 + 0.53MaxAT	0.48
			MinST = 9.65 + 0.78MinAT	0.67

[z] MinST = minimum soil temperature, MaxAT = maximum air temperature, and MinAT = minimum air temperature

models by station locations and associated coefficients of determination (r^2). The r^2 values for those models with daily maximum air temperature as an independent variable (0.42 to 0.73) were consistently lower than that with daily minimum air temperatures (0.53 to 0.84) for all stations. County-wide planting dates were identified each year using the models. For example, in Woodward County, OK, minimum and maximum air temperatures of 12.7 and 24.3 °C, respectively, are needed to raise the minimum soil temperature above 15.6 °C (Fig. 2). Planting date estimates from those models ranged between 1 and 30 April in the Southern High Plains, which are within the typical planting date range (1 April – 10 May) observed in that region (Hake et al., 1993). In general, earlier planting dates were identified for counties located in the eastern half of the study area possibly due to their lower elevation. The later planting dates were commonly found in counties located in the Northern High Plains and the western half of the Central High Plains.

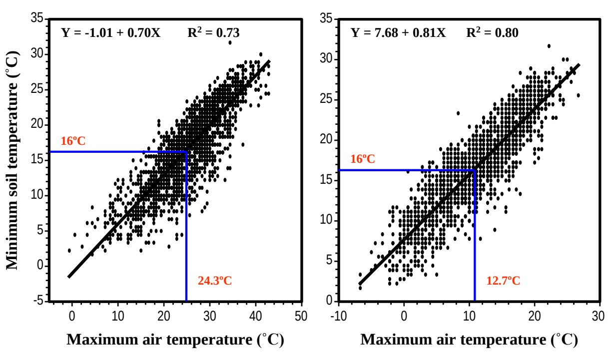

Figure 2. Linear regression models based on minimum and maximum air temperatures for Woodward County, OK.

Total heat units (THU). Figure 3 illustrates the 30-yr county-wide average THU for the study area. For any given longitude within the study area, the THU were higher for southern counties than the northern counties. This is because, the southern counties at a lower latitude are exposed to more direct solar irradiance than that of northern counties and consequently receive more solar energy. Similarly, the THU were higher for counties in the eastern half of the study area compared with counties in the western half. Typically eastern counties were at lower elevation and experienced higher soil and air temperatures that facilitates earlier planting dates. County-wide long-term average THU varied from 582 in the Union County, NM, to 1724 in the Ector County, TX, with an average of 1197 (Fig. 3). Lower accumulation of heat units in the Union County is due to its higher elevation (1816 m) and northern latitude (36.50 °N). In contrast, Ector County is located in the southern most part of the study area with relatively lower elevation (885 m) and latitude (31.88 °N) and consequently recorded higher heat units.

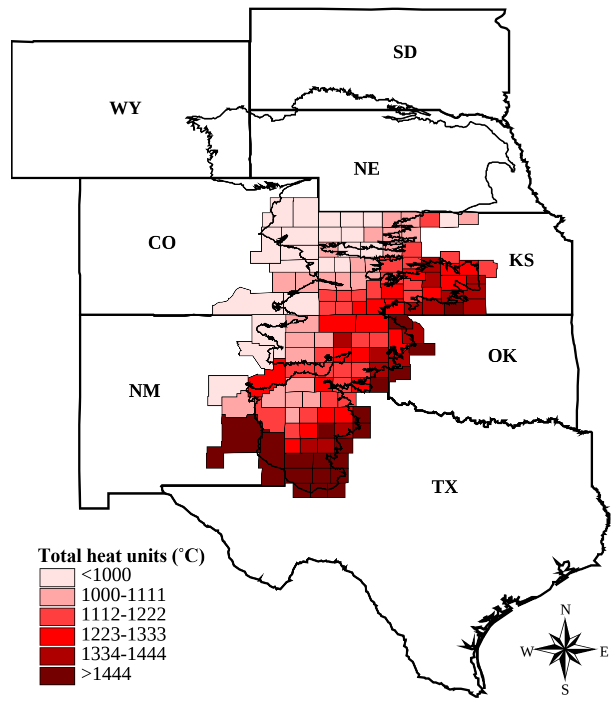

Figure 3. Spatial distribution of countywide long-term (1971-2000) average total heat units (THU) in the study area.

Of 131 counties in the study area, 110 counties including all of the counties in the Texas High Plains except Castro (THU = 998), the Oklahoma Panhandle, and southwestern Kansas recorded 1000 or more HU. Castro County recorded lower long-term average THU than all other counties around it. This may be due to unknown errors in the temperature data for that county. Only two of 10 counties in Colorado recorded THU more than 1000. In this study, a THU of 1000 was used as a cut-off point for determining the feasibility of growing cotton in each county in the study area, because producers of the Texas counties in the Central High Plains have shown that cotton can be grown economically with approximately 1000 heat units (Howell et al., 2004). There were 21 counties in the study area that recorded THU less than 1000. Most of these counties were found either in the Northern High Plains or in the eastern half of the Central High Plains.

Figures 4 and 5 illustrate spatial distribution of county-wide THU that can be expected every year (*P* = 0.99) and in 3 out of every 4 yr (*P* = 0.75), respectively, in the study area. With an every year scenario, the county-wide annual THU varied from 199 to 1633 with an average of 948. Only 40% of all counties in the study area were estimated to have a THU more than 1000. Counties located in southwestern Kansas had THU that ranged from 854-1150. The heat unit accumulation may have been slightly underestimated in these counties, because planting dates for these counties were identified using soil-air temperature relationships developed for Hutchinson station (Fig. 2) with soil temperature data measured at 204 mm depth. The THU exceeded 1444 for only two Texas counties in the Southern High Plains (Table 2). In the 3 out of every 4 yr scenario, the county-wide THU varied from 491 to 1668 with an average of 1109. This is about 161 more HU than that can be expected every year and 88 HU less than the 30-yr (1971-2000) average. These results indicate that producers may have a better chance to increase their net profit with yield goals that can be achieved in 3 out of every 4 yr. This is because cotton produces one more harvestable boll for every additional 41.7 heat units beyond 1000 (Sansone et al., 2002). Seventy-nine counties had estimated THU more than 1000 with 12 of them exceeding 1444 (Fig. 5). In both scenarios, counties located in the eastern half of the study area recorded higher HU than the counties in the western half, which may be partly due to its lower elevation and consequent earlier planting dates.

Table 2. Number of counties with sufficient heat units (HU) for growing cotton using an annually variable based planting and harvest dates

Total heat units (THU; °C)	Number of counties[z]		
	30-yr average THU	Every year (*P* = 0.99)	3 of 4 yr (*P* = 0.75)
≤1000	21	78	40
1000-1111	25	21	31
1112-1222	28	18	23
1223-1333	21	6	17
1334-1444	16	6	8
≥ 1444	20	2	12

[z] The study are includes 131 counties. *P* = exceedance probability calculated as $P = \frac{N}{(n+1)}$, where *N* is the rank of the annual estimated value, and *n* is the total number of years (30).

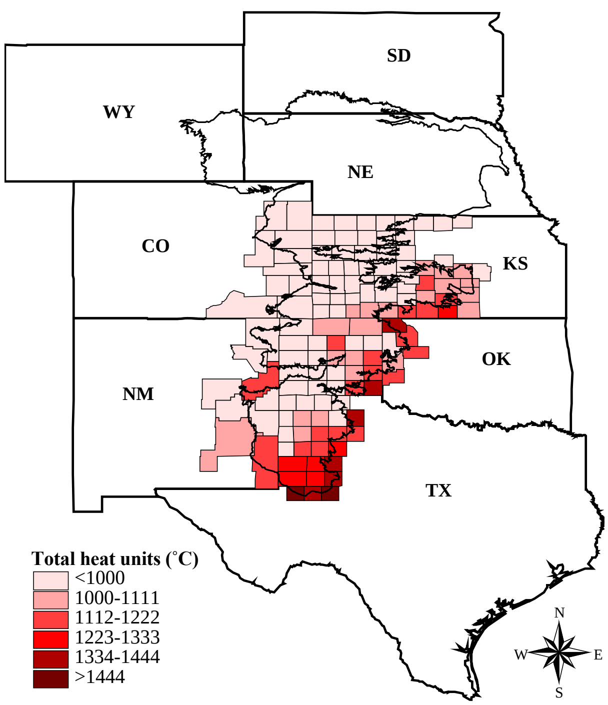

Figure 4. Spatial distribution of countywide annual total heat units (THU) in every year (*P* = 0.99) in the study area.

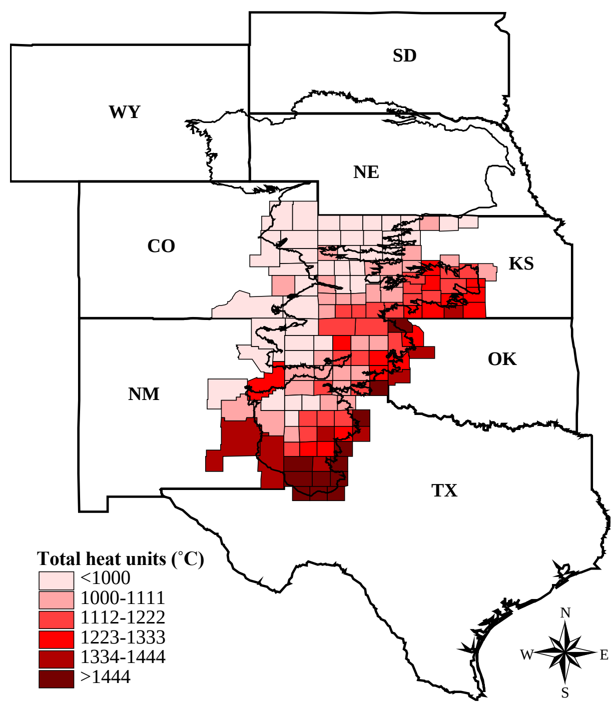

Figure 5. Spatial distribution of countywide annual total heat units (THU) in 3 out of 4 year (*P* = 0.75) in the study area.

CONCLUSIONS

The Ogallala Aquifer is facing declining water levels and one of the options to reduce groundwater withdrawals for irrigation is the adoption of lower water use crops, such as cotton. In this study, the feasibility of growing cotton in the Ogallala Aquifer region was evaluated based on heat unit availability during the growing season. Linear regression models, developed for estimating daily minimum soil temperature from air temperature, were useful for identifying planting dates. Comparisons between three scenarios indicated that long-term THU averages were slightly higher than THU with the 3 out of 4 yr (P = 0.75) scenario. In addition, the number of counties with sufficient THU increased (Table 2) when THU based on long-term averages or 3 out of 4 yr scenario was used as a basis for determining thermal feasibility of cotton production. These results show that cotton is a suitable alternative crop for most counties in southwest Kansas and all counties in the Texas and Oklahoma panhandles; however, management uncertainties on irrigation efficiencies, fertilizer and pest management, planting and harvesting schedule may require further consideration for determining the feasibility to grow cotton. We speculate that there is a potential to reduce annual water withdrawals from the Ogallala Aquifer, if producers converted a part of their corn production land to cotton in counties that receive at least 1000 HU.

DISCLAIMER

Mention of trade names or commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

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