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Spatial and Temporal Variation of Corn Evapotranspiration across Nebraska

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In recent years, water demands for agriculture have been increasing due to the expansion of irrigated acreage, increasing temperatures, increasing competition in domestic, industrial, and environmental sectors, and other factors. In the present scenario, regions that currently do not have water scarcity problems may experience restrictions in their agricultural development—and possibly their food security—due to increases in climatic variability and subsequent reductions in water quantity or water quality degradation. Therefore, reducing the non-beneficial use of water through precise water resource management will help to conserve increasingly scarce water resources.

The efficient use of water resources in agriculture requires adequately quantifying the water requirements for crops, irrigating only when required, and applying an adequate amount of water to prevent stress that may reduce yield and grain quality. Irrigation water requirements are primarily controlled by crop water use or crop evapotranspiration (ETc), precipitation timing and amounts, and available soil water in the crop root zone. The terms "crop water use" and "ETc" are generally used interchangeably to describe the amount of water used by the crop for its growth (and nutrient uptake) under given climatic and soil conditions from planting to physiological maturity.

ETc has an important application in both land surface energy and water budgets. A number of crop, soil, management, and climatic factors influence the amount of crop ETc. For example, different crops reach full canopy cover at different growth stages (different times after planting) and transpire at different rates. A common practice is to use weather station data to calculate potential (reference) ET of a reference crop (ET_{ref}) and then use a crop coefficient (Kc) to adjust the ET_{ref} to estimate the ET of the crop (ETc) of interest.

Two reference crops are typically used for calculating reference ET: alfalfa (commonly used in the Midwestern United States, including Nebraska) and cool season grass (generally used in the eastern U.S. and worldwide). ET_{ref} represents the atmospheric demand for water. Detailed description of monthly, seasonal, and annual ET_{ref} across Nebraska is presented in the University of Nebraska–Lincoln (UNL) publications *Monthly, Seasonal and Annual Spatial and Temporal Variability of Reference (Potential) Evapotranspiration Across Nebraska* (EC2003), and *Magnitude and Trends of Reference Evapotranspiration Rates in South Central Nebraska: Daily, Monthly, Growing Season Total and Annual Total* (EC765). It is assumed that Kc integrates crop height, growth stage, effect of irrigation, and other factors into a single term that is multiplied by the ET_{ref} to estimate the ETc. Detailed explanation of Kc is provided in the UNL Extension publication *Estimating Crop Evapotranspiration from Reference Evapotranspiration and Crop Coefficients* (G1994).

In Nebraska, corn is one of the major row crops. It comprises roughly 44 percent of the total cropland area, and 60.6 percent of the total corn acres is irrigated (USDA-NASS, 2012). Currently, Nebraska ranks No. 1 in the nation in terms of total corn planted under irrigated conditions. *Figure 1* represents the long-term average total corn area under irrigated and rainfed conditions across all 93 Nebraska counties. A majority of the irrigated corn acres are concentrated in the south central portion of the state, which is one of the heaviest irri-

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gated areas in the U.S. For instance, counties such as Fillmore, Adams, Phelps, Clay, Hamilton, Hall, Buffalo, Dawson, York, Polk, and Merrick use irrigation on more than 80 percent of their total area of corn planted, with approximately 65 percent of the total numbers of center pivot irrigation systems also located in central Nebraska (http://snr.unl.edu/data/geography-gis/NebrGISwater.asp#pivot). Rainfed corn is mostly grown in the eastern edge of the state with counties like Richardson, Pawnee, Nemaha, Cass, Washington, Thurston, Dakota, and Dixon having roughly 80 percent of corn planted under rainfed settings where precipitation is generally adequate for plant growth. A detailed monthly, seasonal, and annual distribution of precipitation across Nebraska is presented in the UNL Extension publication EC2002, *Spatial and Temporal Variability of Precipitation across Nebraska* (*Figure 1*).

Seasonal corn ET varies substantially from eastern to western Nebraska (spatial variation) and from year to year (temporal variation) due to climatic conditions, especially precipitation gradient, as well as significant variations in soil types (Sharma and Irmak, 2012a, 2012b). Therefore, considering the extensive irrigated and rainfed agriculture in Nebraska, accurate quantification of spatial and temporal variation of corn ETc under different climates can have significant positive impacts in protecting the quantity and quality of water resources through effective irrigation timing and amount, as well as in substantially enhancing the agricultural productivity. Such analysis and dataset can assist water managers and decision-makers in planning for future demand, use, and availability of water resources for both irrigated and rainfed agriculture.

For this study, the state of Nebraska was divided into four different zones (Zone 1 to Zone 4 from west to east) according to the variability in climatic conditions, soil type, and land use/land cover (*Figure 2*). Also, there is considerable variation in corn planting and harvest dates across the state due to differences in climate gradient from east to west. For example, long-term average precipitation in Zone 1 (western Panhandle area) is 14.38 inches, compared with 27.45 inches in Zone 4 (southeastern Nebraska).

Typically, in Nebraska corn is planted from mid-April to mid-May and emerge within 7 to 10 days under normal weather, soil temperature, and soil moisture conditions. In Zone 1 (semiarid climate), the shorter season/shorter maturity group of crops is planted, and the maturity group of crops planted increases from west to east. Therefore, typical growing season durations of 100 days for Zone 1, 112 days for Zone 2, 120 days for Zone 3, and 140 days for Zone 4 were used in this study.

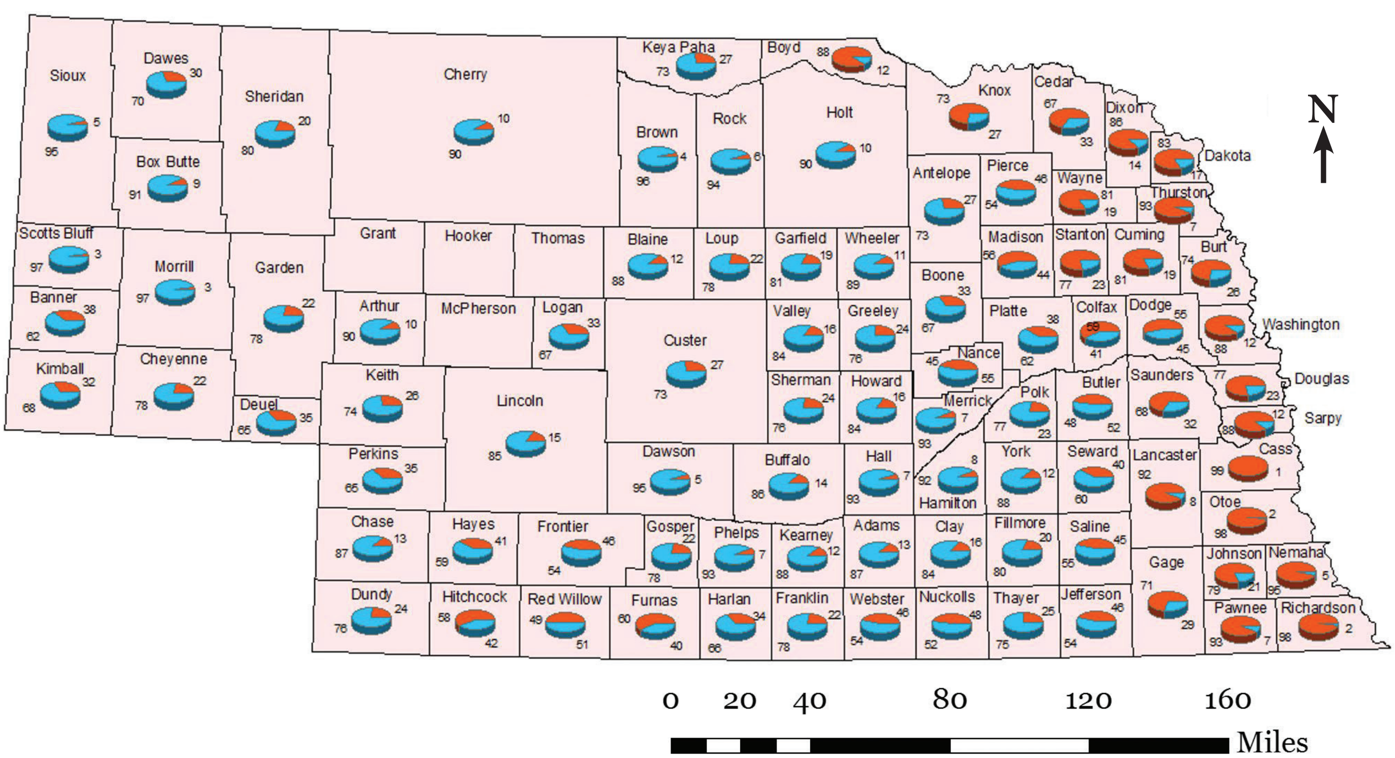

Figure 1. Long-term average percent acreage of irrigated and rainfed corn for all 93 counties across Nebraska. The blue and orange colors in the Nebraska state map represent the percentage of the area under irrigated and rainfed conditions, respectively.

Irrigated and Rainfed Corn Evapotranspiration (ETc)

Corn evapotranspiration (ETc) was estimated with a two-step approach, using the alfalfa-reference evapotranspiration (ET_{ref}) and crop coefficient (Kc), assuming no water stress or disease pressure. Daily climate data (1986–2012) from 50 High Plains Regional Climate Center (HPRCC) Automated Weather Data Network (AWDN) stations across Nebraska was used. From this dataset, ET_{ref} was calculated using the American Society of Civil Engineers (ASCE) Penman-Monteith equation (ASCE-EWRI, 2005) with fixed canopy resistance (Irmak et al., 2012). A detailed description of ET_{ref} calculation is provided in the UNL Extension publication *Monthly, Seasonal, and Annual Spatial and Temporal Variability of Reference (Potential) Evapotranspiration Across Nebraska* (EC2003). In that study, one set of Kc values representing the corn growth and development stages was used to estimate ETc under irrigated conditions.

The corn Kc values used in this study were obtained from long-term field research conducted at the UNL Institute of Agriculture and Natural Resources South Central Agricultural Laboratory near Clay Center, Nebraska, by Suat Irmak. Since the growing season becomes shorter moving from east to west in Nebraska, adjustments were made to account for the differences in the growing season length from Zone 4 to Zone 1. The growing season was assumed to start with the typical or average emergence date of May 1, and physiological maturity was assumed to occur after 100, 112, 120, and 140 days in Zones 1, 2, 3, and 4, respectively.

Under rainfed settings, the corn ETc was estimated using the precipitation and Available Soil Water Holding Capacity (ASWHC) data for each county using the equation developed by Irmak and Sharma (2015):

$$ETcr = P * I + 0.5(ASWHC) \quad (1)$$

where *ETcr* is the growing season rainfed corn evapotranspiration (inch), P is the county mean growing season precipitation (inch); ASWHC is the available soil water holding capacity (inch) in the 4-foot crop root zone for each county's major soil type; and factor *I* is the fraction of precipitation contributing to ETc in rainfed conditions.

Factor *I* was calculated for each zone using the long-term average daily mean, maximum, and minimum air temperature (°F), and the long-term average annual precipitation (inch). Factor *I* was calculated for each HPRCC-AWDN weather station and then averaged to one value for each zone. Detailed description of factor *I* was presented by Irmak and Sharma (2015). Our calculations show that a total of 100 percent, 94 percent, 86 percent, and 76 percent of the growing season precipitation was used for ETc in rainfed conditions in Zones 1, 2, 3, and 4, respectively. For example, in Zone 1, the long-term average seasonal ET_{ref} ranges from 40 to 43 inches, compared with the long-term average precipitation of 6.5 to 9 inches, respectively. Therefore, due to higher atmospheric demand in Zone 1, most of the growing season precipitation is used for ETc due to the prevailing drier conditions as compared with Zones 3 and 4, where in most cases precipitation, with some supplemental irrigation, is adequate for crop production.

A value of 0.5 used in the equation represents the 50 percent depletion in ASWHC for a given soil, at which point crop water stress starts to impact crop yield. Even though this value varies with soil type, texture, and amount of precipitation, it becomes very difficult on a regional scale to account for the variability in all soil types at the finer scale.

Available Soil Water Holding Capacity

The ASWHC also influences crop water use. For example, as soil dries out, it becomes more difficult for the plant to extract water from the soil. At field capacity, plants use water at their maximum rates under ideal conditions. *Figure 2* shows the spatial variation of ASWHC and the four zones across the state. It was calculated as the difference between the field capacity and permanent wilting point summed for each soil layer in the top 4 feet of the soil profile.

The soil properties data from the USDA Natural Resources Conservation Service Soil Survey Geographical Database was used to quantify the ASWHC across the state. However, it is very difficult to account for the variability in each soil type on a regional scale, so for this study ASWHC was calculated considering the major or dominant soil type in each county. The statewide ASWHC in the top 4 feet of the soil profile ranged from 2.2 to 8.2 inches with an average of 5.4 inches.

In general, high ASWHC was observed in south central Nebraska (Zone 3), which has deep silt loam soils containing high organic matter content (OMC), mainly Holdrege or Hastings silt loam (OMC > 2.5%) and Uly-coly silt loam (OMC > 1.5%), with an average volumetric soil moisture content at field capacity and a wilting point of 34 to 35 percent and 13 to 15 percent, respectively, for the Holdrege soil; and 29 to 30 percent and 14 to 15 percent for the Uly-coly soil. Zone 3 had an average ASWHC of 5.91 inches/4 foot with maximum and minimum values of 7.3 to 2.9 inches/4 foot observed in Knox and Loup counties, respectively.

In Zones 1 and 2, the lower ASWHC and lack of precipitation tend to be the limiting factors for crop production, compared with Zones 3 and 4. The average ASWHC in Zone 1 is 4.9 inches/4 foot with a maximum of 6.3 inches/4 foot in Scotts Bluff County and a minimum of 3.1 inches/4 foot in Morrill County. The lowest ASWHC values were observed in the north central part of Zone 2 or the Sandhills, which is an area with sand dunes and temporary and permanent

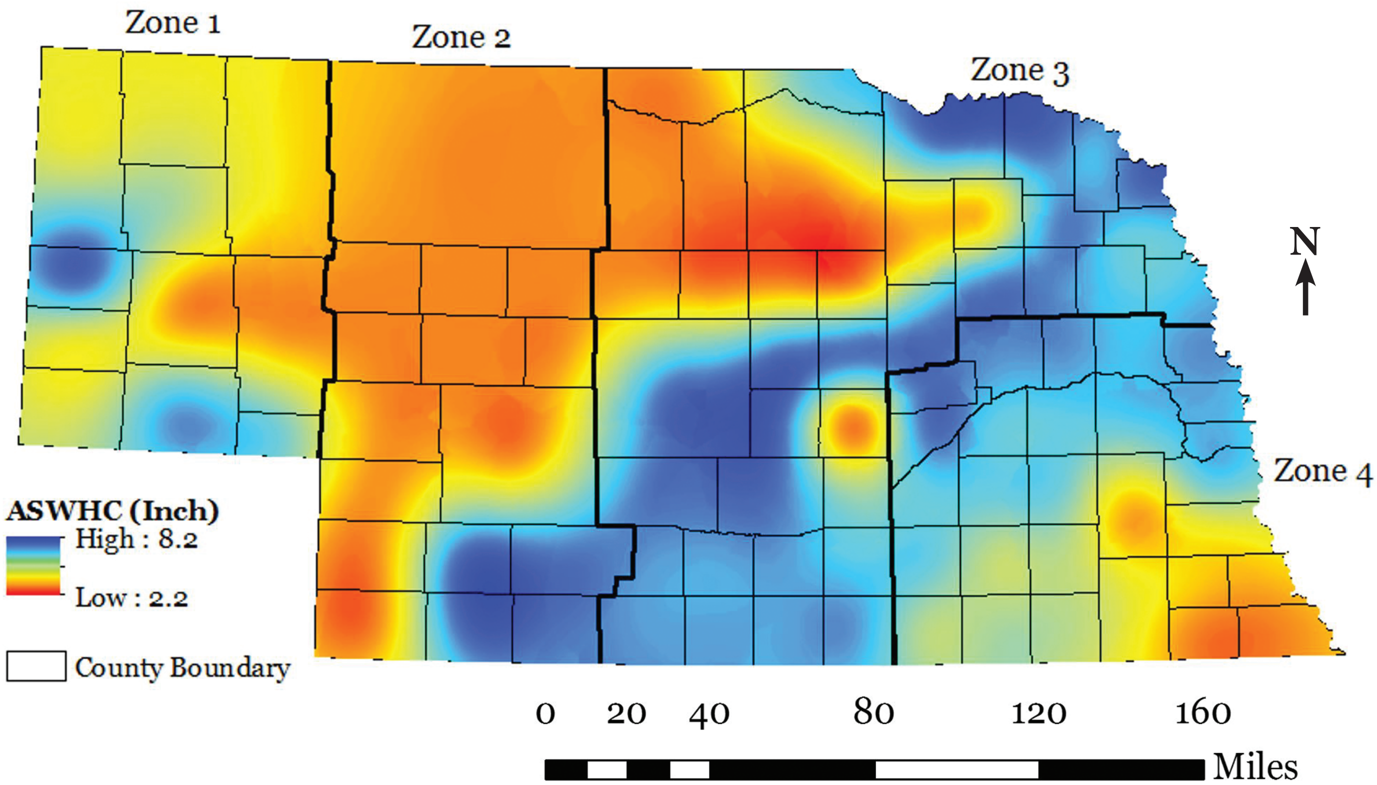

Figure 2. Spatial variability of available soil water holding capacity (ASWHC) in the top 4 feet of soil according to the major or dominant soil type in each county across Nebraska. Darker black lines represent the boundary of the four climatic zones used in this study (Irmak and Sharma, 2015).

TABLE 1. Descriptive statistics for the statewide and zone-wise growing season irrigated and rainfed corn evapotranspiration (ETc, inches) for the period 1986–2012 across Nebraska.

	Average (inch)	*Maximum (inch)*	*County*	*Minimum (inch)*	*County*
Irrigated corn					
Statewide	22.36	26.56	Furnas	19.06	Butler
Zone 1	21.08	21.88	Cheyenne	20.58	Garden
Zone 2	22.56	23.74	Perkins	21.14	Logan
Zone 3	22.30	26.56	Furnas	20.15	Dakota
Zone 4	23.01	26.24	Otoe	19.06	Butler
Rainfed corn					
Statewide	14.20	19.69	Cass	8.87	Banner
Zone 1	10.23	12.15	Deuel	8.87	Banner
Zone 2	12.22	14.27	Hayes	10.91	Dundy
Zone 3	14.11	16.17	Burt	11.45	Keya Paha
Zone 4	16.78	19.69	Cass	15.01	Lancaster

shallow lakes that exist in low lying valleys between the grass-stabilized dunes prevalent in the region.

Spatial Variation of Irrigated and Rainfed Corn Evapotranspiration

Spatial distribution, along with descriptive statistics of long-term (1986–2012) growing season corn ETc under irrigated and rainfed settings across Nebraska, is presented in *Figures 3* and *4* and *Table 1*. A small difference across zones between irrigated corn ETc was noted due to the shorter growing season for Zone 1 (100 days), compared with the longer growing season for Zone 4 (140 days). However, a decreasing irrigated ETc trend was observed from south to north.

For rainfed corn, higher ETc values were observed in eastern Nebraska in Zone 4, with values gradually decreasing toward western Nebraska, following the precipitation trend across the state. For irrigated corn, the long-term (1986–2012) statewide average growing season total ETc ranged from 27 inches in Furnas County (Zone 3) to 19 inches in Butler County (Zone 4), with a long-term statewide average of 22 inches [standard deviation (SD) = 3.9 inches]. The long-term statewide average growing season ETc for rainfed corn was observed as 14 inches (SD = 3.7 inches), with maximum and minimum ETc of 20 inches and 9 inches observed in Cass County (Zone 4) and Banner County (Zone 1), respectively.

On a statewide average basis, irrigated corn ETc was 36 percent higher than rainfed corn ETc. Variability in the growing season ETc totals is influenced by several atmospheric and biological factors. For example, air and surface temperature, vapor pressure deficit, net radiation, leaf area index, and growing degree days play an important role in the ET variability. For more information on vapor pressure deficit influence on ET_{ref} and the long-term trends in vapor pressure deficit, refer to the UNL Extension publication *Long-Term (1893–2012) Changes in Air Temperature, Relative Humidity and Vapor Pressure Deficit (Atmospheric Evaporative Demand) in Central Nebraska* (EC716).

The variability in the magnitude of ETc between the irrigated and rainfed corn crop is due to several factors, including climate and crop characteristics. For example, for irrigated corn the difference in ETc is reflected in the variability in the magnitude of Kc, which is primarily affected by surface conditions and crop characteristics. Under irrigated conditions, the impact of the soil characteristics is not reflected in the crop ET when ETc is calculated using the ET_{ref} and Kc approach. On the other hand, under rainfed conditions the ETc accounts for the variability in precipitation and ASWHC of different soil types across the state.

Zone-wise irrigated and rainfed corn ETc descriptive statistics are presented in *Table 1*. In Zone 1, the long-term average irrigated corn ETc was 21 inches with maximum and minimum values of 22 inches and 20.6 inches observed in Cheyenne County and Garden County, respectively. In contrast, in Zone 4, the long-term average irrigated ETc was 23.01 inches with county averages ranging from 26 inches in Otoe County to 19 inches in Butler County. A small difference of 2 inches was observed in irrigated corn ETc across zones, primarily due to the shorter growing season for Zone 1 (100 days), compared with the longer growing season for Zone 4 (140 days).

On the other hand, under rainfed conditions, lower ETc values were observed across the state. On average, rainfed corn ETc was 49 percent, 46 percent, 37 percent, and 27 percent lower than irrigated corn ETc in Zones 1, 2, 3, and 4, respectively.

To obtain more quantitative assessments of the differences in ETc under irrigated and rainfed conditions, ETc data from 1986 to 2012 from all 93 counties were presented as histogram distributions in *Figure 4*, showing the evident differences between the irrigated and rainfed fields. The ETc data ranged from 12 inches to 36 inches for irrigated corn and from 3.22 inches to 51.1 inches for rainfed corn, with the peak of the histogram observed at 22 inches for irrigated corn and 16 inches for rainfed corn, respectively. Higher rainfed ETc was mainly due to the higher seasonal precipitation that occurred in certain years. For example, the high values of rainfed corn ETc of 51.1 inches were observed in 1993 in Nemaha County, which was one of the wettest years in recorded history in Nebraska with seasonal precipitation of 60 inches.

Temporal Variation of Irrigated and Rainfed Corn Evapotranspiration

Figure 5a, *b*, *c*, *d* shows the time series of the growing season ETc, along with SD values for irrigated and rainfed corn from 1986 to 2012 for each zone. The increasing and decreasing trend is illustrated by the trend lines (solid and dotted black lines) plotted with the time series data. For irrigated corn growing season ETc, a statistically nonsignificant ($P > 0.05$) increasing trend was observed in Zone 2 (slope = 0.026) and Zone 4 (slope = 0.04), and a significant ($P < 0.05$) increasing trend was observed in Zone 3 (slope = 0.134). However, Zone 1 ETc had a decreasing trend with the trend line slope of −0.019.

Overall, there were increases of 0.68, 3.5, and 1.1 inches for Zone 2, Zone 3, and Zone 4, respectively, from 1986 to 2012. Zone 1 had a 0.5 inch decrease in irrigated corn ETc over the same time period. Large fluctuations in ETc between years may be the reason for the nonsignificant increasing and decreasing trends.

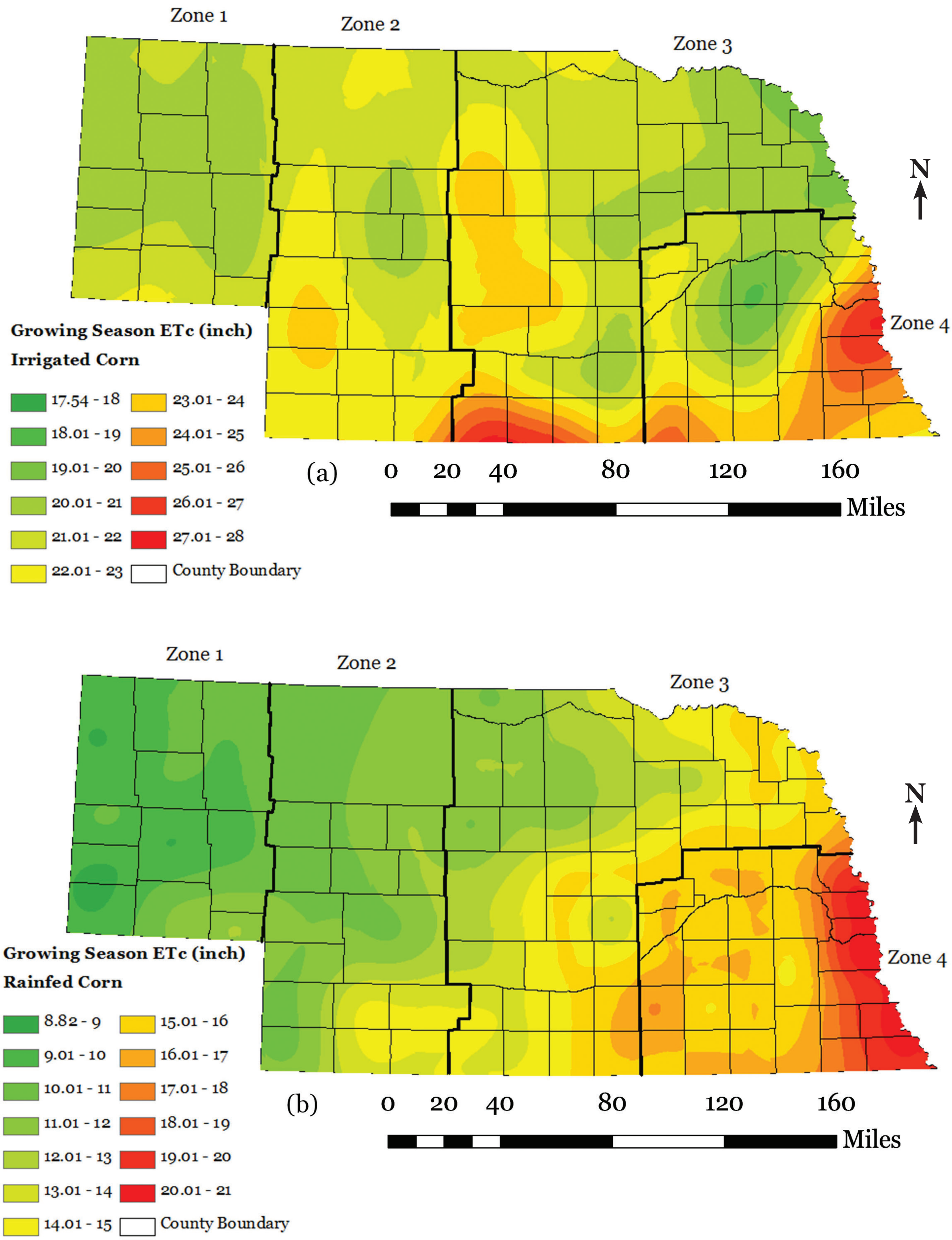

Figure 3. Spatial distribution of long-term (1986–2012) average growing season (a) irrigated and (b) rainfed corn evapotranspiration (ETc, inches) across Nebraska.

Over the 27-year period, the highest irrigated corn ETc was observed in 2012 in Zone 2 (30.1 inches), Zone 3 (32.3 inches), and Zone 4 (30.1 inches). In Zone 1, the highest ETc of 24.1 inches was observed in 2002. Both 2002 and 2012 were record dry years in Nebraska.

The lowest irrigated corn ETc values were observed in the wet years of 2009 for Zone 1 (16.2 inches) and Zone 2 (12.6 inches), and 1992 and 1996 for Zone 3 (16.7 inches) and Zone 4 (16.9 inches), respectively. From 1986–2012, there were 13 years in Zone 1, 14 in Zone 2, 13 in Zone 3, and 14 in Zone 4, where the irrigated corn ETc was greater than the long-term average values of each zone.

Similar to irrigated corn ETc, *Figure 5* represents the temporal variation of rainfed corn ETc from 1986 to 2012. Contrary to irrigated corn ETc, decreasing trends in rainfed ETc were observed in all zones except Zone 3, where ETc had a small increasing trend.

A statistically significant ($P < 0.05$) decreasing trend was observed in Zone 4, where an overall reduction of 5.4 inches in ETc was observed over the span of 27 years. The decreasing trend in Zone 4 was due to lower total seasonal precipitation in recent years. For example, in Zone 4, average precipitation values of 12.3, 13.3, 15.5, 14.8, 13.1, and 8.1 inches were observed in 2002, 2003, 2004, 2005, 2009, and 2012, respectively. All of these values are considerably lower than the long-term average precipitation of 18 inches.

In the UNL Extension publication *Spatial and Temporal Variability of Precipitation across Nebraska* (EC 2002), Irmak and Sharma reported a roughly 7 inch reduction in seasonal precipitation from 1986 to 2012. The highest rainfed corn ETc values of 16.3 inches in Zone 1, 16.9 inches in Zone 2, 21.04 inches in Zone 3, and 27.71 inches in Zone 4 were observed in 2011, 2010, 2010, and 1993, respectively, which were some of the wettest years in Nebraska. The lowest rainfed ETc was observed in 2012.

Summary

In this Extension Circular, long-term spatial and temporal variation in growing season irrigated and rainfed corn evapotranspiration (ETc) is discussed and analyzed. The state was divided into the four climatic zones according to the differences in the climatic, soil, land use/land cover, and topographic characteristics.

Based on the variation in the corn growing season duration across the four zones, it was assumed that the growing

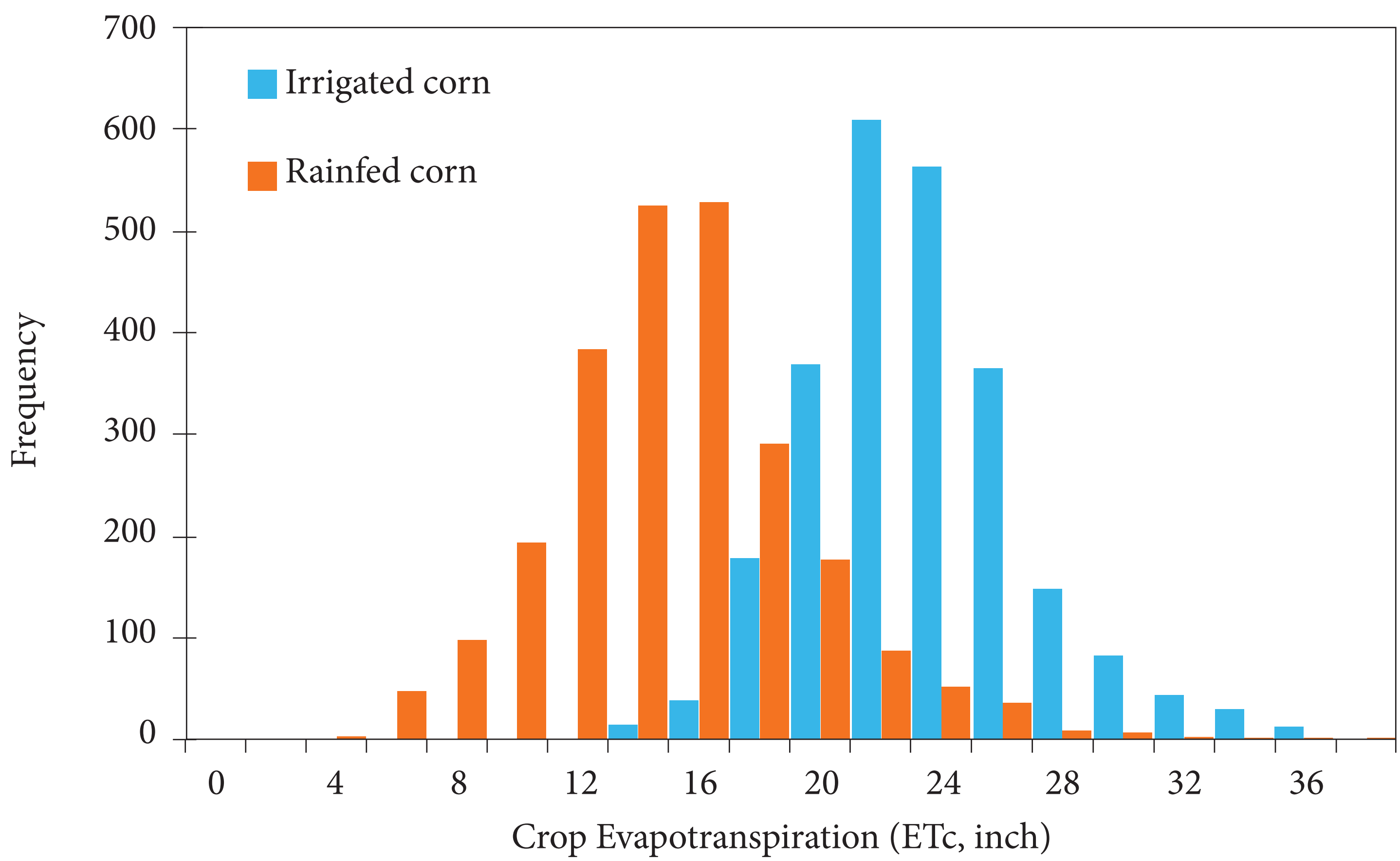

Figure 4. Histogram distribution of irrigated and rainfed corn evapotranspiration (ETc, inch).

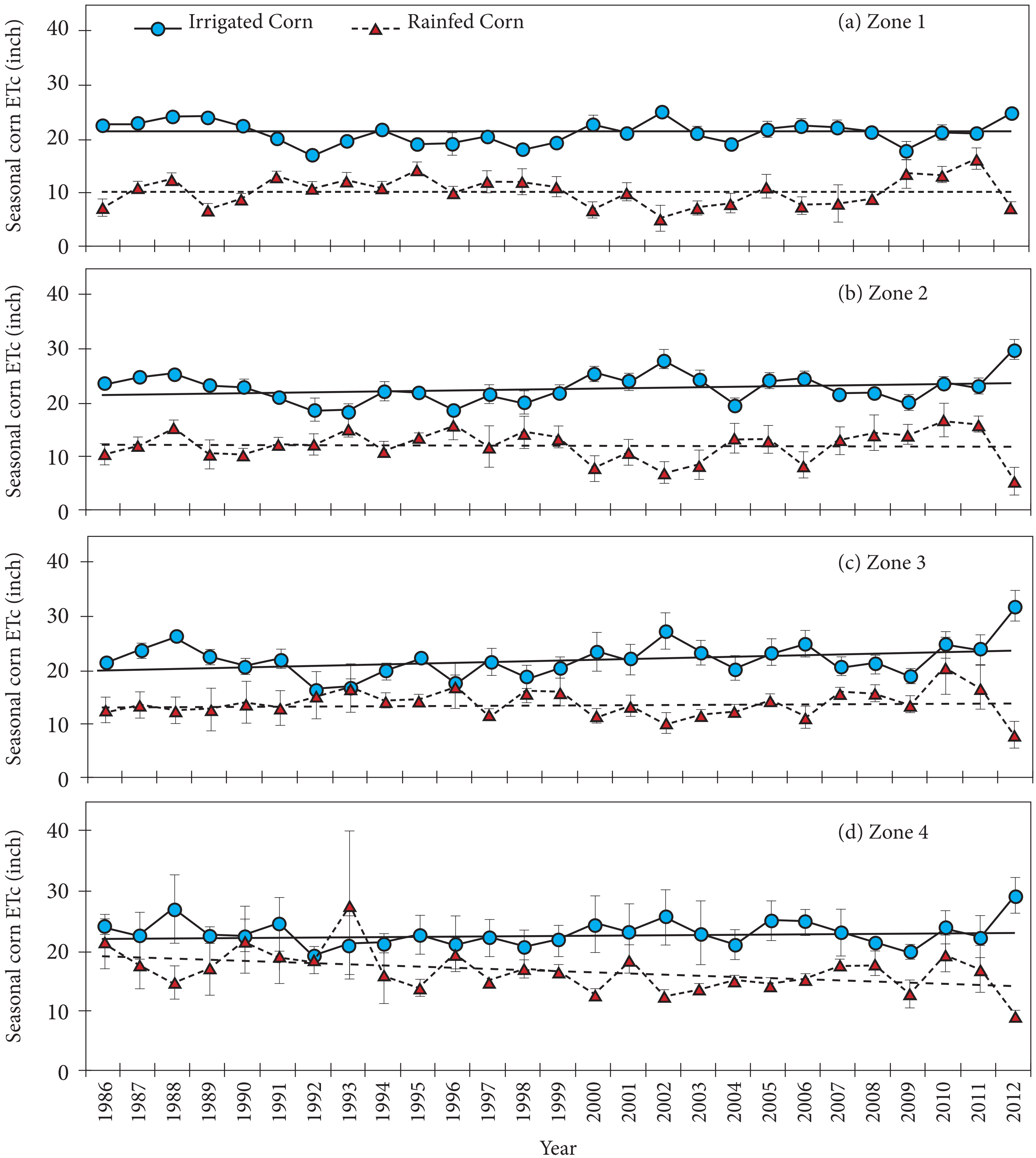

Figure 5. Temporal variation of growing season irrigated and rainfed corn evapotranspiration (ETc) from 1986 to 2012 across Zone 1 (a), Zone 2 (b), Zone 3 (c), and Zone 4 (d) in Nebraska.

season starts with the typical emergence date (May 1) and physiological maturity was assumed to occur after 100, 112, 120, and 140 days in Zones 1, 2, 3, and 4, respectively. Adjustments were made to account for the difference in the growing season length from Zone 4 to Zone 1.

Considering the major or dominant soil type for each county, the statewide ASWHC ranged from 2.2 to 8.2 inches, with an average of 5.4 inches in the top 4 feet of the soil profile. The highest ASWHC was observed in south central Nebraska (Zone 3), and the lowest values were observed in the Sandhills region (Zone 2) of north central Nebraska.

The long-term statewide average growing season ETc of 22 inches (SD = 3.9 inches) and 14 inches (SD = 3.7 inches) was observed for irrigated and rainfed corn, respectively. On a statewide average basis, irrigated corn ETc was 36 percent higher than rainfed corn ETc.

No general trend from east to west was observed for irrigated corn due to the shorter growing season for Zone 1 (100 days), compared with the longer growing season for Zone 4 (140 days). However, for rainfed corn, higher ETc values were observed in eastern Nebraska in Zone 4, with values gradually decreasing toward western Nebraska, following the precipitation trend across the state.

For irrigated corn growing season ETc, an increasing trend was observed in all the zones except for Zone 1, where ETc had a decreasing trend. Overall, irrigated corn ETc from 1986 to 2012 increased by 0.68, 3.5, and 1.1 inches in Zone 2, Zone 3, and Zone 4, respectively, and decreased by 0.5 inches in Zone 1. The highest irrigated corn ETc was observed in 2012 in all zones except Zone 1, where the highest ETc was observed in 2002. In contrast to irrigated corn ETc, decreasing trends in rainfed ETc were observed in all zones except Zone 3, where ETc had a small increasing trend. A decline of 5.4 inches in rainfed ETc was observed in Zone 4 over the 27-year period due to lower total seasonal precipitation in Zone 4, especially in recent years.

This publication has been peer reviewed.

Resources

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