ENVIRONMENTAL CHARACTERIZATION AND WEATHER-RELATED RAINFED MAIZE YIELD-LIMITING FACTORS IN KANSAS, US

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Abstract.
Rainfed maize (Zea mays L.) production in Kansas, located within the United States (US) Great Plains region, is highly sensitive to weather fluctuations. Identifying regions with similar productivity and yield-limiting climatic factors is crucial for developing tailored strategies for those environments. This study aims to delimit environmental regions with similar crop growth conditions and to identify the main climatic factors limiting rainfed maize yield in Kansas. For analysis, data from 1993 to 2021 were compiled, including NOAA weather station data (n = 206), USDA county maize yield data, and crop phenology reports at the agricultural district scale. Four periods were defined based on crop phenology data: the fallow period, the vegetative period, the critical period around flowering (± 15 days), and the grain filling period. Each period included reported climatic variables. Utilizing a Fuzzy c-means clustering algorithm, ten distinct regions were delineated, with grain yields varying between approximately 3500 and 7500 kg ha^{-1}, covering areas from the South-West to the North-East regions. Subsequently, a correlation analysis was performed within each region, examining the relationship between detrended yields and climatic anomalies over 29 years to identify the most significant seasonal climatic factors. The findings reveal that extreme degree days (defined as the accumulation of maximum air temperatures exceeding 35°C) and vapor pressure deficit during the critical period are the main climatic drivers of rainfed maize yield across the regions. This study enhances the understanding of the most relevant climatic drivers of rainfed maize and offers potential applications in other regions for adaptive management strategies and policies.

Keywords.
Zea mays L., Historical climatic variables, Spatial clustering, Yield-limiting factors, U.S. Great Plains.

Introduction:

The Great Plains in the US Corn Belt region, is crucial for maize production. The state of Kansas, located at the Central Great Plains, ranks as the seventh largest producer. In Kansas, 72% of maize is grown under dryland conditions, relying on seasonal precipitation, which makes it vulnerable to drought and climate variability. Maize yields vary significantly across the state, reflecting the precipitation patterns. Water supply is a critical factor in determining maize productivity, especially during the flowering stage, which coincides with high atmospheric water demand in late June and early July. Understanding these climatic influences is essential for developing effective farming management strategies to ensure sustainable maize production.

To address the impact of climate on maize yields in Kansas, it is advantageous to study regions with similar agroecological characteristics and historical trends in crop yields and climatic variables. This helps identify yield-limiting climatic conditions and regions with significant year-to-year fluctuations due to weather extremes (Mourtzinis et al., 2020; Sivakumar & Valentin, 1997). By focusing on climatic variables during critical vegetative and reproductive periods, researchers can better understand their interaction with maize yields (Lu et al., 2017). This probabilistic approach facilitates the development of tailored management strategies suited to specific areas. This study aims to use historical climatic variables, crop phenology, and grain yield data of rainfed maize crops to delineate maize productive regions in Kansas and identify key climatic factors that limit rainfed maize yields in these regions.

Materials and methods:

This study focused on Kansas, located in the Central Great Plains region of the United States, over the period from 1993 to 2021. Daily minimum (Tmin) and maximum (Tmax) temperatures and precipitation data were retrieved from weather stations provided by the National Centers for Environmental Information (NCEI or NOAA) (Chamberlain & Hocking, 2023). The coordinates of these weather stations were used to obtain daily solar radiation and relative humidity data from NASA-POWER (Sparks, 2018). Evapotranspiration (ETo) was computed using the Hargreaves and Samani (1985) methodology, and vapor pressure deficit (VPD) was calculated using daily air temperature and daily relative humidity data. Heat stress occurrence was computed by accumulating maximum air temperatures above 35°C (Extreme degree days, EDD), following the method of Berry and Bjorkman (1980). Weekly crop phenology data were sourced from the National Agriculture Statistics Service Crop Progress Reports (NASS-CPR) of the US Department of Agriculture (USDA) https://www.nass.usda.gov/Statistics_by_State/Kansas/ Publications/Crop_Progress_and_Condition/index.php). Data on non-irrigated maize grain yields in Kansas were obtained from various units within the USDA, including the Risk Management Agency (RMA - https://webapp.rma.usda.gov/apps/ RIRS/AreaPlanHistoricalYields.aspx and the NASS (https://quickstats.nass.usda .gov/).Climatic variables were calculated for different maize growth periods (fallow, vegetative, critical, and grain filling) to assess their impact on grain yield. Given the large number of variables (mean and standard deviation of 24 variables = 48), dimensionality reduction was performed.

All locations were grouped into regions with similar yields influenced by weather variables using the spatial fuzzy c-means (FCM) clustering algorithm (Bezdek et al., 1984). Ten clusters were chosen for regionalization based on the Xie-Beni and Fukuyama-Sugeno indices. Subsequently, correlation analysis was conducted to explore the relationships between climatic variable anomalies at different maize stages and detrended yields within each region, using the Pearson correlation coefficient and p-values.

Results:

The clustering process identified ten distinct regions for rainfed maize production in Kansas. Mean maize grain yield and climatic variables of regions are compared in Table 1. Grain yields span from a minimum of ~3500 kg ha^{-1} to a maximum of ~7500 kg ha^{-1}, from the South-West to the North-East regions. The frost-free period was longer in the southern and eastern regions, with the South-East having the longest period (186 days) and the North-West the shortest (153 days). Annual precipitation increased from West to East, from 495 mm in the South-West to 1132 mm in the South-East. The highest mean temperature during the maize season was in the South-East (22.1 °C), while the lowest was in the North-West (19.9 °C).

Table 1. Grain yield (kg ha^{-1}), climatic conditions (mean of 29 years), and mean dates of crop phenology of 10 regions for rainfed maize production in Kansas. Region data were presented in ascending order of average maize yields. Climatic conditions: frost-free period (days), mean air temperature during the growing season (°C), annual rainfall (mm), and solar radiation (MJ m^{-2} day) during the growing season. Mean values are provided, with corresponding standard deviations enclosed in brackets. Maize crop phenology is described by the mean planting date and silking date per region obtained for the period 1993-2022.

			Growing season (04/01 - 10/30)		Annual	Maize crop phenology	
Region	**Grain yield (kg ha^{-1})**	**Frost-free period (days)**	**Mean season air temperature (°C)**	**Accumulated solar radiation (MJ m^{-2})**	**Rainfall (mm)**	**Average planting date**	**Average silking date**
North - East	7,455 (706)	170 (16)	20.7 (6.7)	3246.4 (140.1)	893 (206)	4-May	14-Jul
East - Central	6,272 (409)	179 (17)	21.2 (6.5)	3251.8 (145.1)	982 (209)	1-May	10-Jul
North - Central	6,178 (510)	169 (17)	20.9 (6.9)	3370.5 (142.1)	747 (182)	6-May	16-Jul
South - East (East)	6,046 (213)	186 (20)	21.8 (6.3)	3265.4 (140.5)	1132 (236)	22-Apr	4-Jul
South - East (West)	5,915 (215)	185 (19)	21.8 (6.4)	3320.2 (140.1)	993 (211)	21-Apr	4-Jul
Central	4,944 (349)	173 (18)	21.5 (7.0)	3438.7 (137.9)	717 (177)	2-May	12-Jul
South - Central	4,493 (484)	183 (18)	22.1 (6.7)	3438.2 (152.4)	802 (194)	2-May	11-Jul
North - West	4,471 (296)	153 (19)	19.9 (7.2)	3541.9 (129.4)	541 (144)	15-May	27-Jul
West - Central	4,199 (235)	160 (19)	20.5 (7.1)	3584.9 (125.2)	536 (138)	14-May	23-Jul
South - West	3,457 (331)	168 (17)	21.3 (6.8)	3669.0 (115.5)	495 (141)	9-May	20-Jul

The correlations between crop yields and climatic variables were explored in previously defined regions during different maize periods (Figure 1). The highest correlation values were obtained when climatic variables were computed during the critical period. For instance, extreme degree days during the critical period (EDD) had the highest correlation with grain across regions (average $r > 0.9$, and p-value < 0.001). Vapor Pressure Deficit during the same period emerged as the second variable during the same period correlated with grain yield (average $r > 0.88$, and p-value < 0.001). Both climatic variables also presented a high correlation with grain yield when they were computed during the grain-filling period. Moreover, the daily thermal amplitude (DTA) has exhibited consistently high average values across all three periods analyzed.

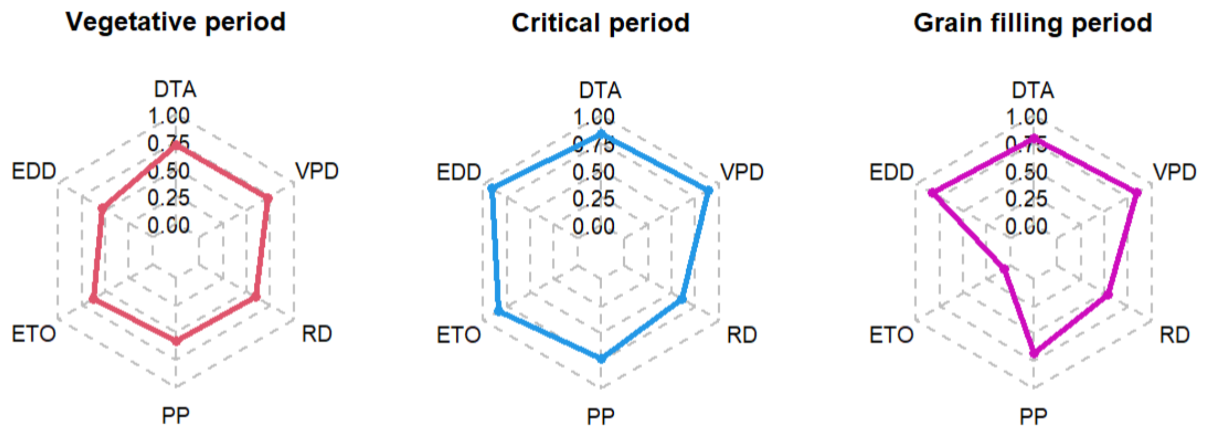

Figure 1: Pearson's r correlation coefficient between detrended rainfed maize yields and anomalies of climatic variables: Extreme degree days (EDD), Vapor pressure deficit (VPD), Evapotranspiration (ET0), Radiation (RD), Daily thermal amplitude (DTA), and Precipitation (PP). These climatic variables were computed during different crop stages (VEG, CP, and GF) for each region based on crop yield and climate data from 1993 to 2021. The r correlation coefficient is expressed as the absolute value of the average across the ten regions previously defined.

Conclusions:

In this study, we have developed a novel methodology for environmental characterization focused on maize grown under rainfed conditions for the state of Kansas within the US Central Great Plains region. These findings offer valuable insights to a wide range of stakeholders, from researchers to policymakers, enabling the development of region-tailored strategies for optimizing rainfed maize production. The approach presented in this study can serve as a framework for directing future research endeavors toward translating these results into actionable recommendations.

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