Drought Characteristics of Major Crops During the Growing Season Across Climate Zones of Inner Mongolia and Regression Models with Response Factors: Postprint

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Abstract

Under the context of global climate change, varying degrees of drought have occurred in various climate zones of Inner Mongolia, which may bring certain disaster losses to local agriculture and animal husbandry. To clarify the drought characteristics during the main crop growing season (May–September) in Inner Mongolia and their response to climate factors, the entire Inner Mongolia region was divided into five climate zones. Monthly meteorological observation data from 46 meteorological stations in Inner Mongolia from 1981–2012 and from 20 meteorological stations from 2014-2020 were selected to calculate the multi-scale Standardized Precipitation Evaporation Index (SPEI) and reveal its drought characteristic patterns. Using the monthly scale as an example, the timing and regions of high drought incidence during the crop growth period in each climate zone were identified, the dominant meteorological factors of drought were determined, and the applicability of regression models was verified. The results show that: (1) In terms of temporal variation, drought conditions were relatively severe from 1998–2008, while drought severity was lighter in other years; (2) Within the crop growing season, drought area and severity were greatest in May; the probability of moderate drought occurrence in the extremely arid climate zone of the west was 37% higher than that in the humid and semi-humid climate zones of the east, while severe drought mainly occurred in the humid and semi-humid climate zones of the east; (3) The dominant meteorological factors of drought in the same month varied across climate zones, with precipitation and minimum temperature being the most important influencing factors of drought during the crop growing season; (4) The estimation models for each climate zone exhibited relatively high accuracy, with errors within a reasonable range; therefore, regression models can be used to estimate monthly SPEI under limited meteorological data conditions. The research results can provide a scientific basis for scientifically assessing drought characteristics during the crop growing season in Inner Mongolia and formulating reasonable drought response measures.

Full Text

Drought Characteristics and Regression Models of Response Factors in Various Climate Zones of Inner Mongolia During the Main Crop Growing Season

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Abstract

Under global climate change, varying degrees of drought have occurred in different climatic zones of Inner Mongolia, potentially causing disaster losses to local agriculture and animal husbandry. To clarify the drought characteristics during the main crop growing season (May–September) and their response to climatic factors, this study divided Inner Mongolia into five climatic zones and selected monthly meteorological observation data from 46 meteorological stations across the region from 1981 to 2012. The Standardized Precipitation Evapotranspiration Index (SPEI) was calculated at multiple time scales to reveal drought characteristics. Using the monthly scale as an example, we identified the timing and regions of high drought incidence during the crop growing season in each climatic zone, determined the dominant meteorological factors driving drought, and validated the applicability of regression models. Results showed that: (1) The drought area and severity were most extensive during the crop growing season. Drought conditions were more severe from 1998 to 2008, while other years experienced relatively mild drought. (2) From a temporal perspective, May showed the most severe drought conditions. The probability of moderate drought in the hyper-arid climate zone of western Inner Mongolia was 37% higher than in the humid and semi-humid zones of the east, while extreme drought occurred mainly in the eastern humid and semi-humid climate zones. (3) The dominant meteorological factors driving drought varied by month and climate zone, with precipitation and minimum temperature being the most important factors affecting drought during the crop growing season. (4) The regression models for each climate zone demonstrated high accuracy with errors within reasonable ranges, indicating that these models can estimate monthly SPEI values when meteorological data are limited. These findings provide a scientific basis for evaluating drought characteristics during the crop growing season in Inner Mongolia and formulating reasonable drought response measures.

Keywords: climate zones; drought characteristics; standardized precipitation evapotranspiration index; meteorological factors; regression models; main crop growing season; Inner Mongolia

Introduction

Global warming directly alters water balance and surface moisture conditions, indirectly triggering meteorological disasters that cause crop yield reductions and ecological degradation. This phenomenon is particularly evident in northern China. Traditional drought indices such as the Standardized Precipitation Index (SPI) and Precipitation Anomaly Percentage only consider precipitation, which has limitations since precipitation is not the sole factor influencing drought. The Palmer Drought Severity Index (PDSI) reduces complex drought phenomena to a single cause and fails to reflect drought mechanisms accurately. While some studies have used these methods to evaluate drought conditions in China, including Inner Mongolia, they are primarily suitable for long-term drought assessment and struggle with short-term drought evaluation.

The Standardized Precipitation Evapotranspiration Index (SPEI) offers advantages by incorporating both precipitation and evapotranspiration, enabling reasonable drought assessment across multiple time scales. Research demonstrates that SPEI based on the Penman-Monteith formula can reasonably describe dry-wet variation characteristics in northern China. Previous studies have analyzed drought spatiotemporal patterns in Inner Mongolia using SPEI, but most have focused on either specific locations or the entire region, with limited attention to drought characteristics and meteorological driving factors during the crop growing season across different climate zones. Clarifying these relationships is crucial for guiding actual agricultural and pastoral production.

This study analyzes drought characteristics and their driving factors during the crop growing season across different climatic zones of Inner Mongolia based on meteorological data from 1981 to 2020 using SPEI. We validate the regression models using 2014-2020 data to identify the timing and specific regions of high drought incidence, revealing drought patterns and mechanisms to provide practical guidance for formulating drought response measures.

1. Materials and Methods

1.1 Study Area Overview and Data Processing

Inner Mongolia is located in northern China, covering 1.183 million km^2, approximately one-eighth of China's total land area. The region spans multiple climate zones with varying drought characteristics and influencing factors. According to the United Nations Convention to Combat Desertification's global aridity index, Inner Mongolia is divided into five climatic zones from west to east: hyper-arid, arid, semi-arid, dry semi-humid, and humid/semi-humid zones.

The study utilized daily meteorological data from 46 stations from 1981 to 2012, including average temperature, maximum temperature, minimum temperature, average wind speed, average air pressure, sunshine hours, average relative humidity, and precipitation. [Figure 1: see original paper] shows the distribution of all meteorological stations. Due to data discontinuities at Jikede, Alxa Right Banner, Hangjin Rear Banner, and Yijinhuoluo Banner stations, drought analysis for 1981–2012 used data from 42 stations. For model validation from 2014 to 2020, data from 20 evenly distributed stations were used.

1.2.1 Standardized Precipitation Evapotranspiration Index (SPEI)

The SPEI calculation involves several steps:

Step 1: Calculate potential evapotranspiration (PET) using the Penman-Monteith formula:

$$PET = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

where R_n is net radiation at the crop surface ($\mathrm{MJ \cdot m^{-2} \cdot d^{-1}}$), G is soil heat flux density ($\mathrm{MJ \cdot m^{-2} \cdot d^{-1}}$), T is mean air temperature (°C), u_2 is wind speed at 2 m height ($\mathrm{m \cdot s^{-1}}$), e_s is saturation vapor pressure (kPa), e_a is actual vapor pressure (kPa), Δ is the slope of the vapor pressure curve ($\mathrm{kPa \cdot {}^{\circ}C^{-1}}$), and γ is the psychrometric constant ($\mathrm{kPa \cdot {}^{\circ}C^{-1}}$).

Step 2: Calculate climatic water balance as the difference between monthly precipitation and evapotranspiration:

$$D_i = P_i - PET_i$$

where i is the monthly sequence in the study period, P_i is precipitation (mm), and PET_i is potential evapotranspiration (mm).

Step 3: Establish water surplus/deficit at different time scales:

$$D_n^k = \sum_{i=0}^{k-1}(P_{n-i} - PET_{n-i})$$

where k is the monthly time scale and n is the calculation frequency.

Step 4: Calculate probability weighted moments, probability density function parameters, and cumulative probability. Details are provided in Li Weiguang et al. [citation].

Step 5: Normalize the SPEI series to obtain the final SPEI values:

$$SPEI = W - \frac{c_0 + c_{1W} + c_{2W}^2}{1 + d_{1W} + d_{2W}^2 + d_{3W}^3}$$

where $W = \sqrt{-2\ln(P)}$ for $P \leq 0.5$, and $P = 1 - F(x)$. Constants are $c_0 = 2.515517$, $c_1 = 0.802853$, $c_2 = 0.010328$, $d_1 = 1.432788$, $d_2 = 0.189269$, and $d_3 = 0.001308$.

1.2.2 Drought Classification Standards

SPEI has multi-time scale characteristics. This study calculated SPEI at 1-, 3-, 6-, and 12-month scales for 42 stations. Drought classification follows the standards shown in .

SPEI drought rating criteria | SPEI Value | Drought Category | |———|———— | | > -0.5 | No drought | | -1.0 < SPEI ≤ -0.5 | Mild drought | | -1.5 < SPEI ≤ -1.0 | Moderate drought | | -2.0 < SPEI ≤ -1.5 | Severe drought | | ≤ -2.0 | Extreme drought |

1.2.3 Extraction of Drought Characteristics and Regression Model Validation

The main crop growing season in Inner Mongolia is May–September. This study analyzed drought characteristics using monthly SPEI-1 values, which reflect current month conditions without excessive influence from non-growing season precipitation.

Multiple linear regression was used to establish stepwise linear regression models between SPEI-1 and meteorological factors (precipitation, temperature, relative humidity, sunshine hours, wind speed, air pressure) to identify dominant factors and their path coefficients. Models were validated using 2014–2020 data through error analysis, including Mean Relative Error (MRE), Root Mean Squared Error (RMSE), Nash-Sutcliffe Efficiency Coefficient (NSE), and Regression Coefficient (b):

$$MRE = \frac{1}{N}\sum_{i=1}^{N}\left|\frac{P_i - O_i}{O_i}\right| \times 100\%$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(P_i - O_i)^2}$$

$$NSE = 1 - \frac{\sum_{i=1}^{N}(O_i - P_i)^2}{\sum_{i=1}^{N}(O_i - \bar{O})^2}$$

where N is the number of observations, P_i and O_i are predicted and observed values, and $\bar{O}$ is the mean observed value. Model performance improves as R^2 and b approach 1, MRE and RMSE approach 0, and NSE approaches 1. Models with NSE > 0.5 are considered feasible.

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2. Results

2.1 Multi-Time Scale Drought Characteristics in Inner Mongolia (1981-2020)

[Figure 2: see original paper] shows SPEI variations at different time scales. At short time scales (SPEI-1, SPEI-3), SPEI fluctuates significantly, reflecting short-term water balance changes. At longer time scales (SPEI-6, SPEI-12), fluctuations are smoother with more apparent lag effects. From 1981-2020, drought was more severe during 1998-2008, with drought events occurring annually, primarily concentrated in May-September, overlapping with the main crop growing season. The region experienced a drought transition from mild to severe and back to mild, particularly in 1999-2002 when drought severity was most pronounced with overall SPEI values lower than other periods.

2.2 Drought Characteristics During the Main Crop Growing Season

[Figure 3: see original paper] shows interannual variations in monthly average SPEI-1 during the growing season. Among 40 years, 21 years showed drought conditions (SPEI-1 $<$ -0.5). Severe and extreme droughts occurred in 1981, 1986, 1989, 1992, 1999-2002, and 2007. May is the critical period for crop emergence and jointing; drought during this stage significantly impacts yield reduction.

[Figure 4: see original paper] shows the average percentage of drought area during the growing season. Drought area and severity peaked in May, gradually decreasing thereafter. The probability of no drought was 31.2%, mainly in eastern and central-eastern humid regions. Mild drought occurred with 36.7% probability in central, central-western, and western regions. Moderate drought probability was 21.6% in hyper-arid zones—37% higher than in humid/semi-humid zones. Severe drought probability was 7.5% across all regions, while extreme drought paradoxically occurred more frequently in eastern humid regions (3.0% probability).

[Figure 5: see original paper] shows average drought area percentages by climate zone. The hyper-arid zone had the highest drought probability, followed by arid, semi-arid, dry semi-humid, and humid/semi-humid zones. [Figure 6: see original paper] shows monthly precipitation and potential evapotranspiration. Although precipitation peaked in July, evapotranspiration also reached its annual maximum, resulting in severe water deficits. Monthly precipitation was consistently lower than evapotranspiration throughout the growing season, causing persistent drought conditions.

[Figure 7: see original paper] shows spatial distribution of drought frequency. Key drought-prone areas include Alxa in western Inner Mongolia, Hetao Irrigation District, Baotou, Zurihe, Abag Banner, and Hulunbuir in the east. Drought frequency decreased from west to east. Temporally, drought was most severe during early crop growth stages (May–June).

2.3 Dominant Meteorological Factors Driving Drought During the Growing Season

Kolmogorov-Smirnov tests confirmed that SPEI-1 values followed normal distributions across all climate zones and periods (), enabling regression analysis. Stepwise linear regression between SPEI-1 and meteorological factors yielded high determination coefficients ().

Overall, precipitation and minimum temperature were the primary factors affecting SPEI-1. However, dominant factors varied by month and climate zone ():

- **May**: Minimum temperature and precipitation
- **June**: Minimum temperature, wind speed, and air pressure
- **July**: Wind speed, relative humidity, and sunshine hours
- **August**: Minimum temperature
- **September**: Minimum temperature, wind speed, and relative humidity
- **Growing season average**: Relative humidity, minimum temperature, and sunshine hours

Standardized coefficients revealed that minimum temperature had greater influence than other temperature variables. While precipitation and relative humidity were crucial, their high correlation prevented simultaneous inclusion in models.

2.4 Validation of Regression Models for Each Climate Zone

Models were validated using 2014–2020 data. [Figure 8: see original paper] shows predicted versus calculated SPEI-1 values, which distributed evenly around the 1:1 line, indicating high model precision. Error analysis () showed:

- **Moist/semi-humid zone**: MRE = -0.1%, RMSE = 0.15, NSE = 0.98
- **Dry semi-humid zone**: MRE = -0.4%, RMSE = 0.17, NSE = 0.97
- **Semi-arid zone**: MRE = 0.2%, RMSE = 0.16, NSE = 0.97
- **Arid zone**: MRE = 0.3%, RMSE = 0.18, NSE = 0.96
- **Hyper-arid zone**: MRE = 0.1%, RMSE = 0.19, NSE = 0.95

All climate zone models showed high accuracy, while the regional average model performed less precisely (NSE = 0.89). May and growing season average models had lower accuracy than other months due to more severe and complex drought conditions.

3. Discussion

This study reveals that rising temperatures directly impact drought during the crop growing season. Consistent with Huang et al. [citation], climate change has caused both decreased precipitation and increased evapotranspiration in Inner Mongolia, particularly in central and eastern regions where extreme drought probability is higher. The region shows a decreasing precipitation trend, especially in central-eastern areas, affecting water resources.

Previous research on drought drivers in Inner Mongolia has focused on large-scale analysis, lacking precision for agricultural guidance. This study demonstrates that dominant meteorological factors vary by month and climate zone, enabling more accurate local agricultural guidance. The high correlation between precipitation and relative humidity required variable removal during regression, which is a methodological consideration.

The study focuses on meteorological drought and its relationship with climatic factors to provide a basis for agricultural drought prevention and irrigation planning. Future research should integrate meteorological drought with soil drought to better guide agricultural production.

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4. Conclusions

1. **Interannual variation**: Inner Mongolia experienced a drought transition from mild to severe (1998–2008) and back to mild. Drought was most severe during 1999–2002.
2. **Temporal patterns**: May showed the largest drought area and severity during the crop growing season. The probability of moderate drought in hyper-arid zones was 37% higher than in humid/semi-humid zones. Extreme drought probability was 3.0%, paradoxically higher in eastern humid regions.
3. **Dominant factors**: Precipitation and minimum temperature were the primary drought drivers, though specific factors varied by month and climate zone. Minimum temperature was the most consistent influential factor across zones.
4. **Model performance**: Regression models for each climate zone demonstrated high accuracy (NSE > 0.95) and can estimate monthly SPEI with limited meteorological data, providing theoretical support for drought analysis when data are incomplete.

References

[1] Dai A, Trenberth K E, Qian T. A global dataset of Palmer Drought Sever-

ity index for 1870-2002: Relationship with soil moisture and effects of surface warming[J]. Journal of Hydrometeorology, 2004, 5(6): 1117-1130.

[2] Zheng Dawei, Li Maosong, Huo Zhiguo. Agricultural Disasters and Countermeasures for Disaster Reduction[M]. Beijing: China Agricultural University Press, 2013.

[3] Ma Zhuguo, Fu Congbin. Characteristics of aridification over northern China during 1951-2004[J]. Chinese Science Bulletin, 2006, 51(20): 2429-2439.

[4] Zhou Dan, Zhang Bo, Luo Jing, et al. SPEI based intensity characteristics and cause analysis of drought in North China during recent 50 years[J]. Journal of Natural Disasters, 2014, 23(4): 192-202.

[5] Hayes M J, Svoboda M D, Wilhite D A, et al. Monitoring the 1996 drought using the standardized precipitation index[J]. Bulletin of the American Meteorological Society, 1999, 80(3): 429-438.

[6] Liu Ronghua, Zhu Zixi, Fang Wensong, et al. Risk regionalization of yield loss caused by drought for winter wheat in North China Plain[J]. Chinese Journal of Ecology, 2006, 25(9): 1068-1072.

[7] Zhou Lei, Wu Jianjun, Lv Aifeng, et al. Drought evolution of different land cover regions in North China[J]. Geographical Research, 2012, 31(4): 597-607.

[8] Wu Yingjie, Li Wei, Wang Wenjun, et al. Drought characteristics in Inner Mongolia based on precipitation anomaly percentage[J]. Arid Zone Research, 2019, 36(4): 943-952.

[9] Zhu Ye, Jin Xintong, Liu Yi, et al. Drought characteristics analysis in China based on self-calibrating Palmer drought severity index in a short time scale[J]. Water Resources Protection, 2022, 38(4): 124-130.

[10] Wang Lin, Chen Wen. Applicability analysis of standardized precipitation evapotranspiration index in drought monitoring in China[J]. Plateau Meteorology, 2014, 33(2): 423-431.

[11] Vicente-Serrano S M, Begueria S, Lopez-Moreno J I. A multiscalar drought index sensitive to global warming: The standardized precipitation evapotranspiration index[J]. Journal of Climate, 2010, 23(5): 611-618.

[12] Wang Na, Wang Jing, Feng Liping, et al. Modeling the impact of Double Delay technology on yield of wheat-maize cropping system in the North China Plain[J]. Chinese Journal of Agrometeorology, 2015, 36(5): 611-618.

[13] Liu Ke, Jiang Dabang. Analysis of dryness/wetness over China using standardized precipitation evapotranspiration index based on two evapotranspiration algorithms[J]. Chinese Journal of Atmospheric Sciences, 2015, 39(1): 23-36.

[14] Zhuang Shaowei, Zuo Hongchao, Ren Pengcheng, et al. Application of standardized precipitation evapotranspiration index in China[J]. Climatic and Environmental Research, 2013, 18(5): 617-625.

[15] Li Weiguang, Yi Xue, Hou Meiting, et al. Standardized precipitation evapotranspiration index shows drought trends in China[J]. Chinese Journal of Eco-Agriculture, 2012, 20(5): 643-649.

[16] Liu Yu, Li Wenqing, Liu Zhao, et al. Spatial and temporal evolution characteristics of the drought in Weibei loess tableland area based on SPEI[J]. Research of Soil and Water Conservation, 2021, 28(1): 109-117.

[17] Zhang Xuting, Pan Xuebiao, Xu Lin, et al. Analysis of spatiotemporal distribution of drought characteristics based on SPEI in Inner Mongolia during 1960-2015[J]. Transactions of the Chinese Society of Agricultural Engineering, 2017, 33(15): 190-199.

[18] Li Chongrui, You Songcai, Wu Yongfeng. Drought characteristics and dominant meteorological factors driving drought in spring maize growing season in Northeast China[J]. Transactions of the Chinese Society of Agricultural Engineering, 2020, 36(19): 97-106.

[19] Liu S, Kang W, Wang T. Drought variability in Inner Mongolia of northern China during 1960-2013 based on standardized precipitation evapotranspiration index[J]. Environmental Earth Sciences, 2014, 72(7): 2505-2515.

[20] Ren Xiaodong. Assessment of ET_0 Estimation Methods (FAO PM Temperature and Hargreaves-Samani Methods) in Different Climates of Inner Mongolia[D]. Hohhot: Inner Mongolia Agricultural University, 2014.

[21] Allen R G, Pereira L S, Raes D, et al. Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements[M]. Rome, Italy: FAO Irrigation and Drainage, 1998: 56.

[22] Wang Xiaoxiao, Pan Xuebiao, Gu Shenghao, et al. Trend in reference crop evapotranspiration and meteorological factors affecting trends in Inner Mongolia[J]. Transactions of the Chinese Society of Agricultural Engineering, 2015, 31(Suppl.1): 142-152.

[23] Huang J, Sun S L, Xue Y, et al. Changing characteristics of precipitation during 1960-2012 in Inner Mongolia, northern China[J]. Meteorology and Atmospheric Physics, 2015, 127(3): 257-271.

[24] Na Yintai. Drought characteristics in Inner Mongolia based on the SPI index in the last 50 years[J]. Journal of Arid Land Resources and Environment, 2015, 29(5): 161-166.

[25] Li Qiuyue, Pan Xuebiao, Wang Li, et al. Analysis of the trend of climate resources change in Inner Mongolia[J]. Chinese Journal of Agrometeorology, 2011, 32(Suppl.): 19-23.

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