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Spatiotemporal Variation of Drought and Its Climatic Response in the Xilingol Region, 2000-2018: Postprint

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Abstract

The Temperature Vegetation Dryness Index (TVDI) is an important method for reflecting drought conditions. Taking Xilingol in Inner Mongolia Autonomous Region as the study area, and based on the Temperature Vegetation Dryness Index, this study employs trend analysis and R/S analysis methods to investigate the spatiotemporal variation characteristics of TVDI in the Xilingol region from 2000 to 2018 and the influence of climatic factors such as precipitation and temperature on TVDI changes. The results show that: (1) During the 19-year period, the deviation value of TVDI exhibited a trend of first decreasing and then increasing, with the average TVDI value being 0.55 and the TVDI value ranging from 0.51 ~ 0.61, indicating that the Xilingol region as a whole was in a state of mild drought. (2) During the 19-year period, the area with a significant increase in TVDI accounted for 9.48% of Xilingol region, while the area with a slight increase accounted for 18.52%, with the increasing trend mainly distributed in the northeastern part of East Ujimqin Banner; the area with a significant decrease in TVDI accounted for 28.65%, and the area with a slight decrease accounted for 9.03%, with the decreasing trend primarily observed in Sonid Right Banner, Sonid Left Banner, Abag Banner, and Xianghuang Banner. Over the past 19 years, the change trend in the Xilingol region has been: stronger in the east than in the west. The average Hurst index value was 0.44, with areas greater than 0.44 accounting for 47.7% of the total area, indicating that overall drought persistence is slightly weaker than anti-persistence. (3) The correlation between TVDI and annual mean temperature was weak, while there was a strong correlation with monthly mean temperature.

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Full Text

Temporal and Spatial Variations of Drought and Climatic Response in the Xilingol Grassland from 2000 to 2018

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Abstract

The Temperature Vegetation Dryness Index (TVDI) serves as a crucial method for characterizing drought conditions. Taking Xilingol League in Inner Mongolia as the study area, this research investigates the spatiotemporal variation characteristics of TVDI from 2000 to 2018 and its climatic response to precipitation and temperature using trend analysis and the Hurst index method. The study reveals that: (1) The average TVDI value for the region was 0.55, with values ranging from 0.51 to 0.61, indicating that Xilingol was generally in a state of light drought. The deviation of TVDI showed a trend of first decreasing then increasing. (2) Areas with significantly increasing TVDI accounted for 18.52% of the total area, primarily distributed in the northeastern part of East Ujimqin Banner; areas with significantly decreasing TVDI accounted for 9.48%, mainly in Sonid Right Banner, Sonid Left Banner, Abag Banner, and Xianghuang Banner. (3) The spatial variation trend was stronger in the eastern region than in the western region. (4) TVDI showed weak correlation with annual mean temperature but strong correlation with monthly mean temperature. (5) The overall drought persistence was slightly weaker than anti-persistence.

Keywords: Temperature Vegetation Dryness Index; Spatiotemporal variation; Xilingol; Hurst index

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1.1 Study Area Overview

Xilingol League is located in central Inner Mongolia, between 115°13 -117°06 E and 43°02 -44°52 N, characterized by a north temperate continental climate with strong winds, aridity, and cold temperatures. The average annual precipitation is approximately 300 mm, decreasing from southeast to northwest, with rainfall concentrated in the summer months of June through August. Annual evaporation ranges from 1,500 to 2,700 mm, and the relative humidity is low. The region features diverse grassland types from west to east: desert steppe, sandy grassland, typical steppe, and meadow steppe, constituting a major component of Inner Mongolia' s grassland ecosystem.

1.2 Data Sources and Processing

The primary remote sensing data source consisted of MODIS products from 2000 to 2018, including the MOD11A2 land surface temperature product and MOD13A2 vegetation index product, both with 1 km spatial resolution. Data preprocessing involved using MODIS Reprojection Tools (MRT) for batch processing of format conversion, mosaicking, and reprojection, followed by clipping to the study area boundary and removal of outliers. The MOD11A2 8-day product was synthesized using the maximum value compositing method to reduce cloud, atmospheric, and solar zenith angle effects, while the MOD13A2 16-day NDVI product was similarly processed. Finally, the highest and lowest temperatures corresponding to the same NDVI intervals were extracted to construct the temperature-vegetation dryness index product.

Meteorological data were obtained from the China Meteorological Data Service Center' s monthly surface climate dataset (http://data.cma.cn), including temperature and precipitation data from six stations within Xilingol: Sonid Left Banner, East Ujimqin Banner, West Ujimqin Banner, Duolun County, Abag Banner, and Xilinhot City.

2.1 Vegetation Index-Land Surface Temperature Feature Space

Sandholt et al. demonstrated that in the NDVI-Ts feature space, a series of soil moisture isolines exist, where the slope between the two parameters is negatively correlated with soil moisture. Based on this principle, the Temperature Vegetation Dryness Index was developed to indirectly represent soil moisture conditions. TVDI is calculated from vegetation index and land surface temperature extracted from remote sensing imagery, defined as:

$$TVDI = \frac{T_s - T_{min}}{T_{max} - T_{min}}$$

where T_s is the land surface temperature of any pixel, T_{max} is the temperature on the dry edge (maximum land surface temperature for pixels with a given NDVI value), and T_{min} is the temperature on the wet edge (minimum land surface temperature for pixels with a given NDVI value). The dry and wet edges can be calculated through linear fitting:

$$T_{max} = a \times NDVI + b$$

$$T_{min} = c \times NDVI + d$$

where a, b, c, and d are model parameters obtained through linear fitting. Higher TVDI values indicate lower soil moisture, more severe water deficiency, and higher drought intensity, while lower values suggest better moisture conditions.

2.2 Trend Analysis

Trend analysis simulates the change trend for each raster cell, reflecting TVDI variation within the time series and thereby analyzing drought changes. The linear regression slope is calculated as:

$$Slope = \frac{n \times \sum_{k=1}^{n} k \times Y_k - \sum_{k=1}^{n} k \times \sum_{k=1}^{n} Y_k}{n \times \sum_{k=1}^{n} k^2 - (\sum_{k=1}^{n} k)^2}$$

where k represents the year sequence number, Y_k is the TVDI value in year k, and n is the sample size. A positive slope indicates a drying trend, while a negative slope indicates a wetting trend.

2.3 Rescaled Range Analysis (R/S Analysis)

Rescaled range analysis is a quantitative method for describing the long-term dependency of time series data. The Hurst exponent (H) has become a standard metric for quantifying long-term persistence in sample data. For a time series $TVDI(t)$, the mean sequence is defined, followed by calculation of cumulative deviation, range sequence, and standard deviation sequence. The Hurst exponent is obtained through least squares fitting in a double logarithmic coordinate system.

The Hurst exponent ranges from 0 to 1. When $H = 0.5$, the TVDI change trend is random with no long-term correlation. When $H < 0.5$, future TVDI trends will be opposite to past trends (anti-persistent). When $H > 0.5$, future trends will be consistent with past trends (persistent).

3.1 Spatiotemporal Variation Characteristics of Drought

Based on the interannual TVDI variation in Xilingol, the region experienced light drought conditions with an average TVDI of 0.55 and values ranging from 0.51 to 0.61. Deviation analysis reveals that TVDI deviations first decreased then increased, with the maximum value occurring in 2014 (exceeding the mean by 9.48%) and the minimum in 2010 (below the mean by 9.03%). The overall trend showed fluctuations with an upward trajectory at a rate of 9.48% per decade.

In terms of drought severity classification, light drought occupied the largest proportion (47.7%), with drought-affected areas exceeding 90% of the total region, indicating significant impacts on pastoral activities. The spatial distribution exhibited clear horizontal zonation, with TVDI gradually increasing from east to west, corresponding to vegetation type distribution. Areas with moderate TVDI values were primarily in the western and west-central regions (desert steppe), while high TVDI values occurred in the central-eastern typical steppe. The lowest TVDI values were concentrated in the northeastern part of East Ujimqin Banner (meadow steppe), indicating wetter conditions.

Intra-annual variation showed the driest conditions from January to April (TVDI > 0.6, severe drought), particularly in Xilinhot and parts of East Ujimqin Banner. TVDI decreased from April to June, fluctuated between June and October within the light drought range, then increased and decreased again from October to December, reaching its minimum in August.

3.2 Drought Change Trend and Prediction

Based on the linear regression model at pixel scale, areas with increasing and decreasing TVDI trends accounted for 56.1% (113,647 km^2) and 43.9% (88,932 km^2) of the total area, respectively. According to statistical significance tests, significantly increasing areas comprised 18.52%, primarily in northeastern East Ujimqin Banner; significantly decreasing areas comprised 9.48%, mainly in Sonid Right Banner, Sonid Left Banner, Abag Banner, and Xianghuang Banner; and slightly decreasing areas comprised 28.65%.

The average Hurst index was 0.44, with values greater than 0.44 covering 47.7% of the area, indicating that overall drought anti-persistence was slightly stronger than persistence. By superimposing the Hurst index spatial pattern with the slope change trend, future TVDI trends were classified into five categories: anti-persistent increase, persistent increase, no persistence, persistent decrease, and anti-persistent decrease. Anti-persistent increase areas accounted for 23.07%, while anti-persistent decrease areas accounted for 45.51%, primarily distributed in Sonid Right Banner, Xianghuang Banner, and Zhengxiangbai Banner. Persistent decrease areas comprised 26.79%, mainly along the northeastern edge of East Ujimqin Banner and in Xilinhot.

3.3 Impact of Temperature and Precipitation on TVDI

To investigate relationships between meteorological factors and TVDI, this study analyzed interannual variations of temperature and precipitation and their correlations with TVDI. Annual precipitation in Xilingol fluctuated between 170-320 mm with an increasing trend, while annual mean temperature ranged from 2-12°C, also showing a significant increasing trend. Both trends passed significance tests at the 0.05 level.

TVDI showed negative correlations with both annual and monthly precipitation, with determination coefficients of 0.42 and 0.68, respectively, both significant at the 0.05 level. While TVDI correlated weakly with annual mean temperature, it showed strong correlation with monthly mean temperature ($R^2 = 0.61$). Buffer zone analysis around meteorological stations confirmed these relationships, indicating that precipitation and monthly temperature are the primary meteorological factors influencing TVDI variation in Xilingol.

4 Discussion

This study demonstrates that TVDI effectively characterizes drought conditions in Xilingol. The combination of trend analysis and R/S analysis provides more precise exploration of drought change trends compared to previous studies that relied on single-temporal remote sensing data. The results align with Chen et al.' s findings on TVDI applicability in Xilingol grassland, showing similar drought distribution ranges, intensity levels, and development processes during the study period, with drought concentrated in eastern regions and lower drought levels in western areas.

However, this analysis only considered meteorological factors (precipitation, temperature) without incorporating topographic, vegetation, or land cover effects, which also influence soil moisture conditions and may introduce bias in TVDI results. Future research should integrate these underlying surface factors to improve drought monitoring accuracy. Additionally, under decreasing soil moisture conditions, vegetation growth may face severe stress, warranting further investigation.

5 Conclusions

From 2000 to 2018, Xilingol experienced light drought conditions with an average TVDI of 0.55 (range: 0.51-0.61). TVDI deviation showed a decreasing-then-increasing pattern, peaking in 2014 (+9.48% above mean) and reaching minimum in 2010 (-9.03% below mean), with an overall upward trend of 9.48% per decade. Drought-affected areas exceeded 90% of the region, with light drought covering 47.7% of the area.

Spatially, TVDI increased from east to west, corresponding to grassland type distribution. Temporally, the driest period occurred January–April, while the wettest conditions appeared August–October. Trend analysis revealed 56.1% of the area showed increasing drought trends and 43.9% showed decreasing trends, with significant increases concentrated in northeastern East Ujimqin Banner and significant decreases in Sonid Right/Left Banners, Abag Banner, and Xianghuang Banner.

The average Hurst index of 0.44 indicated that anti-persistence slightly exceeded persistence. Future trends showed 23.07% of the area in anti-persistent increase and 45.51% in anti-persistent decrease. Meteorological analysis revealed that while precipitation and temperature both increased significantly during the study period, TVDI was negatively correlated with precipitation (annual and monthly) and strongly correlated with monthly temperature but only weakly with annual temperature.

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