Soil Moisture Variations in the Guanzhong Region and Their Response to Climate: Postprint

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Abstract

Abstract: The Guanzhong region is the primary agricultural production base in Shaanxi Province, yet recurrent droughts have severely impeded socioeconomic development. Soil moisture serves as a crucial indicator reflecting drought conditions; research on the response of soil moisture to climatic factors can provide a scientific basis for understanding drought patterns and policy formulation. Taking the Guanzhong region as the study area, this study constructs a characteristic space of surface soil moisture conditions (TVDI) using long-term time series data of MODIS-NDVI and MODIS-LST from 2001 to 2020, and analyzes the spatial distribution characteristics of soil moisture conditions and their response to climate employing statistical methods including linear trend analysis, correlation analysis, and sensitivity analysis. The results indicate: (1) TVDI can relatively accurately retrieve soil moisture conditions in the Guanzhong region. Over the past 20 years, soil moisture conditions in the Guanzhong region have exhibited a drying trend; among seasons, spring is the driest, followed by winter. (2) The spatial distribution of soil moisture conditions exhibits significant spatial heterogeneity, showing an overall trend of increasing drought severity from southwest to northeast. (3) Soil moisture conditions are correlated with precipitation and temperature. There is a positive correlation with precipitation: as precipitation increases, soil moisture increases; there is a negative correlation with temperature: as temperature rises, soil moisture decreases. (4) Precipitation exhibits high sensitivity to soil moisture conditions, while temperature exerts a substantial influence on the magnitude of change in soil moisture conditions. Precipitation determines the direction of increase or decrease in soil moisture values, whereas temperature determines the magnitude of such increase or decrease. Soil moisture conditions constitute a comprehensive indicator, and its values are influenced by both precipitation and temperature. Precipitation is the primary factor determining the trend of increase or decrease in values, while temperature determines the amplitude of such increase or decrease. Therefore, when examining only the effects of temperature and precipitation, precipitation

is the main factor controlling the trend of increase or decrease in soil moisture conditions, while temperature modulates the amplitude of such increase or decrease.

Full Text

Preamble

Changes in Soil Moisture and Dryness and Their Response to Climate in the Guanzhong Region

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Abstract: The Guanzhong region serves as the primary agricultural production base in Shaanxi Province, yet frequent drought disasters severely hinder socioeconomic development. Soil moisture, a crucial indicator for drought monitoring, provides essential insights for scientifically understanding drought patterns and formulating effective policies. This study focuses on the Guanzhong region, utilizing long-term MODIS-NDVI and MODIS-LST time series data to construct the Temperature-Vegetation Dryness Index (TVDI) characteristic space. Linear trend analysis, correlation analysis, sensitivity analysis, and other statistical methods were employed to examine the spatial distribution characteristics of soil moisture and dryness conditions and their response to climate factors. Results demonstrate that: (1) TVDI can accurately retrieve soil moisture conditions in the Guanzhong region. Over the past two decades, the region has exhibited a drying trend, with spring being the driest season followed by winter. (2) Significant spatial heterogeneity exists in soil moisture distribution, showing an overall pattern of increasing drought severity from southwest to northeast. (3) Soil moisture correlates positively with precipitation (soil moisture increases as precipitation increases) and negatively with temperature (soil moisture decreases as temperature rises). (4) Precipitation shows high sensitivity to soil moisture conditions, while temperature substantially influences the magnitude of change in soil moisture status. Precipitation determines the direction of soil moisture change (increase or decrease), whereas temperature determines the degree of change. Soil moisture conditions represent a comprehensive indicator influenced by both precipitation and temperature, with precipitation primarily controlling the trend direction and temperature regulating the magnitude of change. Therefore, when examining the effects of temperature and precipitation, precipitation emerges as the dominant factor controlling soil moisture trends, while temperature modulates the amplitude of these changes.

Keywords: soil moisture and dryness conditions; temperature vegetation index; precipitation; temperature; Guanzhong region

Introduction

Soil moisture constitutes the primary factor affecting plant growth, directly determining vegetation distribution and crop yields, while also serving as a key parameter in land-atmosphere interactions that significantly influence climate change. Traditional soil moisture monitoring relies on ground observation stations, which, despite high precision, suffer from uneven distribution, poor representativeness, and high resource consumption, making large-area monitoring impractical. The increasing availability of remote sensing data has enabled widespread application of remote sensing-based soil moisture retrieval methods, leveraging advantages such as broad coverage and rapid update frequency.

Since 1978, when the thermal inertia model was first applied to remotely monitor soil moisture conditions, limitations regarding high-precision diurnal temperature difference data have prompted development of alternative methods, including vegetation index approaches and microwave remote sensing. The Temperature-Vegetation Dryness Index (TVDI), a vegetation index method based on long-term NDVI and LST time series data, has proven effective for precise drought monitoring by utilizing the characteristic space formed by these two parameters. TVDI effectively reflects drought characteristics and has been widely applied in soil moisture monitoring.

In the Guanzhong region, numerous scholars have employed TVDI for drought research. Wang Pengxin et al. [?] demonstrated that TVDI effectively monitors soil moisture conditions, with results correlating well with soil thermal inertia model retrievals. Zhang Jingyan et al. [?] found that the Weihe Plain experiences more severe drought conditions than the southern Qinling region, particularly in Weinan, with TVDI providing reliable drought monitoring for the region. He Huijuan et al. [?] analyzed spatiotemporal drought distribution using MOD16 products, further validating TVDI' s applicability.

The Guanzhong region, a socioeconomically and agriculturally developed area in Shaanxi Province, experiences frequent, prolonged, and destructive droughts due to its inland location far from oceanic influences, with substantial spatial variation in drought occurrence. Recent climate warming has intensified soil degradation and drought events, severely impacting the regional agricultural ecosystem and environment. Timely, accurate, and large-scale monitoring of drought development patterns is therefore crucial for guiding agricultural production in the Guanzhong region.

This study employs MODIS data from 2001 to 2020, utilizing linear trend analysis, correlation analysis, partial correlation analysis, t-tests, and sensitivity analysis to examine spatiotemporal patterns, trends, and responses to precipitation and temperature, providing theoretical support for scientifically managing drought and adjusting agricultural practices.

1. Study Area Overview

The Guanzhong region, located in central Shaanxi Province along the middle and lower reaches of the Weihe River, spans 106°18 ~110°37 E and 33°35 ~35°50 N. Administratively, it includes five cities and one district: Xi' an, Baoji, Xianyang, Weinan, Tongchuan, and the Yangling Demonstration Zone. The region is bounded by the Qinling Mountains to the south and separated from northern Shaanxi by the Ziwu and Huanglong Mountains to the north [Figure 1: see original paper]. Characterized by a continental monsoon climate, the area experiences humid summers with abundant rainfall and dry winters with minimal snowfall, representing a transitional zone between warm temperate semi-humid and semi-arid climates. The multi-year average temperature ranges from 6 to 13°C, with average annual precipitation of 500–700 mm.

2. Data and Methods

2.1 Data Sources and Processing

Remote sensing data included MODIS products (MOD11A2 and MOD13Q1) obtained from NASA' s LAADS website (ladsweb.modaps.eosdis.nasa.gov/), with spatial resolutions of 1 km and 500 m, and temporal resolutions of 8 days and 16 days, respectively. Data preprocessing involved mosaicking, projection conversion, and format conversion using the MRT tool, followed by maximum value compositing to generate annual datasets. Meteorological data comprised annual average temperature and precipitation for the Guanzhong Plain from 2001 to 2020, sourced from the Chinese Academy of Sciences' Resource and Environmental Science Data Center (https://www.resdc.cn/) at 1 km resolution. Digital elevation model data were obtained from the Geospatial Data Cloud (http://www.gscloud.cn) as SRTM DEM.

2.2 Methodology

2.2.1 Soil Moisture and Dryness Retrieval Soil moisture conditions are influenced by multiple factors with complex interactions. Previous studies [**?**] combined NDVI and LST to construct the TVDI characteristic space for soil moisture estimation. Based on this characteristic space, TVDI is expressed as:

$$\text{TVDI} = \frac{\text{LST} - \text{LST}_{\text{min}}}{\text{LST}_{\text{max}} - \text{LST}_{\text{min}}}$$

where LST represents land surface temperature; LST_{min} represents the minimum surface temperature corresponding to a given NDVI value (the wet edge); and LST_{max} represents the maximum surface temperature (the dry edge). TVDI ranges from 0 to 1, with higher values indicating drier soil conditions.

This study utilized MATLAB to create a graphical user interface (GUI) for establishing the Guanzhong region' s TVDI characteristic space. Analysis of the annual soil moisture characteristic space diagrams (2001–2020) reveals that the dry and wet edge equations exhibit similar fitting characteristics each year, generally forming triangular or trapezoidal patterns consistent with Wang Hanwen et al. [?]. As NDVI increases, LST_{min} decreases linearly, while LST_{max} shows greater fluctuation.

Based on established drought classification systems [?], this study categorizes soil moisture conditions in the Guanzhong region into five classes using TVDI: extremely wet ($0 \leq$ TVDI < 0.2), wet ($0.2 \leq$ TVDI < 0.4), normal ($0.4 \leq$ TVDI < 0.6), dry ($0.6 \leq$ TVDI < 0.8), and severely dry ($0.8 \leq$ TVDI ≤ 1).

2.2.2 Linear Trend Analysis Linear regression was applied to the retrieved TVDI data (2001–2020) to analyze trends:

$$\hat{y}_i = \theta_{\text{slope}} \times t_i + b$$

where $\hat{y}_i$ represents the fitted soil moisture value; t_i represents the time corresponding to year i; θ_{slope} represents the regression coefficient; and b represents the constant term. The parameters are estimated using least squares:

$$\theta_{\text{slope}} = \frac{n \sum (t_i \times \text{TVDI}_i) - \sum t_i \sum \text{TVDI}_i}{n \sum t_i^2 - (\sum t_i)^2}$$

where n represents the study period length (20 years), and $\overline{\text{TVDI}}$ and $\bar{t}$ represent the mean values. The F-test was employed to assess trend significance, with $\theta_{\text{slope}} > 0.01$ indicating increasing drought severity, $\theta_{\text{slope}} < -0.01$ indicating decreasing drought severity, and $-0.01 \leq \theta_{\text{slope}} \leq 0.01$ indicating stable conditions.

2.2.3 Correlation Analysis Pearson correlation analysis first examined relationships between soil moisture and climate factors (precipitation, temperature). Partial correlation analysis then quantified individual climate factor impacts [?], with t-tests assessing significance.

The Pearson correlation coefficient is calculated as:

$$r_{xy} = \frac{\sum_{i=1}^{n} (x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum_{i=1}^{n} (x_i - \overline{x})^2 \sum_{i=1}^{n} (y_i - \overline{y})^2}}$$

where n represents the time series length, and x_i, y_i represent annual pixel values for variables x and y.

Partial correlation coefficients among the three variables (soil moisture, precipitation, temperature) were calculated as:

$$r_{xy\cdot z} = \frac{r_{xy} - r_{xz}r_{yz}}{\sqrt{(1-r_{xz}^2)(1-r_{yz}^2)}}$$

where $r_{xy\cdot z}$ represents the partial correlation between variables x and y while controlling for z.

T-tests for partial correlation significance used:

$$t = \frac{r_{xy\cdot z}}{\sqrt{1-r_{xy\cdot z}^2}} \times \sqrt{n-m-1}$$

where m represents the number of independent variables and n represents the sample size.

2.2.4 Sensitivity Analysis Sensitivity coefficients quantified soil moisture response to climate factors:

$$S = \lim_{\Delta x \to 0} \left(\frac{\Delta \text{TVDI}}{\Delta x} \right) = \frac{\partial \text{TVDI}}{\partial x}$$

where S represents the sensitivity coefficient of TVDI to climate factor x. Larger $|S|$ values indicate greater climate influence. The contribution rate (C_i) of meteorological factor i to soil moisture change is:

$$C_i = S_i \times R_{ci}$$

where $R_{ci} = \frac{|\text{Trend}_i|}{\overline{x_i}} \times 100\%$ represents the relative change of climate factor i, with Trend_i indicating linear trend change and $\overline{x_i}$ representing the multi-year mean absolute value.

3. Results and Analysis

3.1 Validation of Soil Moisture Retrieval Results

TVDI has been widely applied with high monitoring accuracy. To validate our results, we selected 0-10 cm soil moisture monitoring data from national agricultural meteorological stations, as numerous scholars have confirmed TVDI effectively reflects surface soil moisture status [?]. Validation using March and July 2009 data yielded a correlation coefficient of -0.68 (P $\leq$ 0.05), indicating significant negative correlation and good agreement [Figure 3: see original paper]. These results confirm that TVDI reliably retrieves soil moisture conditions in the Guanzhong region.

3.2 Spatiotemporal Characteristics of Soil Moisture

3.2.1 Temporal Variation Characteristics Annual variation analysis reveals that since 2001, the Guanzhong region has experienced varying drought severity, with an overall mean TVDI of 0.62 indicating dry conditions. The most severe drought occurred in 2001 (TVDI = 0.68), with other years fluctuating around 0.62 [Figure 4: see original paper].

Seasonal analysis shows spring (March–May) as the driest season (mean TVDI = 0.71, severely dry), with high variability but consistently within 0.76–0.925. Summer (June–August) and autumn (September–November) exhibit similar patterns as the wettest periods (TVDI = 0.3-0.5, wet level). Winter (December–February) patterns closely resemble annual averages. Spring shows the strongest decreasing trend ($-0.0024 \cdot a^{-1}$), while autumn is the only season with increasing soil moisture ($+0.0012 \cdot a^{-1}$). The annual decreasing trend ($-0.0015 \cdot a^{-1}$) primarily results from spring and winter moisture reduction, with spring contributing slightly more than winter.

The relationship between soil moisture and vegetation is evident: spring vegetation growth extracts soil water during low rainfall periods, while summer peak vegetation growth coincides with maximum precipitation, creating water surplus. Autumn vegetation senescence reduces water demand despite continued precipitation, maintaining wet conditions. Winter dormancy with reduced precipitation leads to dry conditions [Figure 5: see original paper].

3.2.2 Spatial Distribution and Trends Spatial distribution from 2001–2020 shows a clear pattern of increasing drought from southwest to northeast. Peak drought areas (TVDI > 0.8, severely dry) concentrate along the Weihe River valley, particularly in central Weinan (Pucheng, Chengcheng, Heyang counties). Minimum values (TVDI < 0.2, extremely wet) occur in Taibai County, Baoji. Higher soil moisture corresponds to higher elevations with forest or grassland land use, while lower moisture appears in low-elevation cultivated areas along the Weihe River. Enhanced continental climate trends in eastern Guanzhong, particularly Weinan, explain the extensive severe drought distribution [**?**].

Trend analysis reveals that 52.8% of the region experienced drying trends, while 16.2% showed wetting trends. The central Weihe River valley primarily exhibits increasing drought severity, while southwestern and northeastern areas show decreasing trends. Significant wetting occurs in Longxian (Baoji), JinTai District, and northeastern Zhouzhi County (Xi' an), with significant drying concentrated at the intersection of Dali, Linwei, and Pucheng counties in Weinan. After F-test significance testing (threshold $|t| > 4.41$ at $\alpha = 0.05$), five trend categories were established: significant wetting, insignificant wetting, stable, insignificant drying, and significant drying [Figure 6: see original paper] [Figure 7: see original paper].

3.3 Soil Moisture Response to Precipitation and Temperature

3.3.1 Correlation Analysis As the primary water source, precipitation significantly influences soil moisture. Correlation analysis (2001–2020) shows positive correlation dominating (61.7% of area), with 18.9% being significantly positive. Negative correlations appear sporadically in Baoji (Fengxiang) and Xianyang (Binzhou, Changwu), Weinan (Fuping, Dali, Tongguan, Huayin), comprising only 7.8% of the area. Partial correlation analysis, controlling for temperature, shows similar positive dominance (45.5% of area), with the correlation area decreasing by 16.2% compared to simple correlation, indicating temperature' s moderating effect on precipitation' s influence [Figure 8: see original paper].

Temperature exhibits predominantly negative correlation with soil moisture (75.5% of area), with only 24.5% positive correlation. After controlling for precipitation, partial correlation shows 66.8% negative correlation area, a 16.2% reduction from simple correlation, indicating precipitation' s moderating effect on temperature's influence. This negative correlation creates a positive feedback loop: temperature increase enhances evapotranspiration, reducing soil moisture and increasing sensible heat, further elevating surface temperature. Unchecked, this process leads to progressive soil desertification.

3.3.2 Sensitivity Analysis Sensitivity analysis reveals that soil moisture is highly sensitive to both precipitation (S_p) and temperature (S_t), with precipitation sensitivity coefficients exceeding temperature coefficients across all regions and seasons. Seasonally, precipitation sensitivity ranks as autumn > spring > winter > summer, while temperature sensitivity ranks as summer > spring > winter > autumn, consistent with regional climate characteristics .

Regional sensitivity rankings for both precipitation and temperature follow: Baoji > Xianyang > Xi' an > Weinan. This pattern reflects the influence of Mount Taibai (the highest peak in the Qinling Mountains, located in Taibai County, Baoji), which receives the most precipitation and lowest temperatures in the region.

Contribution rate analysis shows temperature as the dominant contributor to soil moisture changes annually. Seasonally, temperature contributions exceed precipitation in winter and spring, while contributions are roughly equivalent in summer, and precipitation dominates in autumn .

In summary, precipitation sensitivity coefficients determine the direction of soil moisture change (increase or decrease), while temperature contribution rates determine the magnitude of change. Precipitation controls whether soil moisture increases or decreases, while temperature determines the degree of change, with both factors jointly controlling soil moisture dynamics.

4. Conclusion and Discussion

This study utilized MODIS remote sensing data (2001–2020) and TVDI to monitor long-term soil moisture changes in the Guanzhong region, yielding the following conclusions:

1) TVDI effectively retrieves soil moisture conditions in the Guanzhong region, which exhibits an overall drying trend with spatial patterns of peripheral areas being wetter than central areas, southern areas wetter than northern areas, and drought severity increasing from southwest to northeast. During 2001–2020, the rate of soil moisture decrease significantly exceeded the rate of increase.

2) Soil moisture correlates positively with annual precipitation and negatively with annual temperature. Cross-interactions exist between precipitation and temperature effects on soil moisture, with temperature' s interaction effect exceeding that of precipitation.

3) Sensitivity analysis indicates soil moisture is more sensitive to precipitation than temperature. However, temperature shows higher contribution rates than precipitation annually. Temperature contributions exceed precipitation in spring and winter, are roughly equivalent in summer, and are lower than precipitation in autumn. Precipitation controls the direction of soil moisture change, while temperature determines the magnitude of change, with both jointly controlling soil moisture dynamics.

While TVDI effectively monitors soil moisture, actual conditions are influenced by multiple factors including climate, elevation, land use, soil physicochemical properties, and soil depth, with inherent periodic variations. Analysis limited to two climate factors cannot fully explain all soil moisture variations. Future research should integrate multiple influencing factors to comprehensively understand soil moisture dynamics and better guide regional agricultural production.

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Note: Figure translations are in progress. See original paper for figures.