Remote Sensing Monitoring of Soil Drought Integrating GPM Precipitation Data (Postprint)

Authors: Tan Huizhi, Yin Qian

Date: 2021-04-23T00:00:00+00:00

Abstract

Global climate warming has exacerbated drought trends, posing a severe threat to agricultural and pastoral production in northwestern arid and semi-arid regions. Considering that Shenmu City in Shaanxi Province exhibits typical Loess Plateau geomorphological characteristics, and that precipitation plays a decisive role in drought formation in areas with complex geomorphological backgrounds, this study employs high-precision GPM (Global Precipitation Measurement) precipitation data to establish a remote sensing monitoring model for soil drought, conducting applied analytical research capable of revealing relative soil moisture. Results indicate that: the integrated vegetation-temperature-precipitation soil drought remote sensing monitoring model constructed using GPM precipitation data can accurately reveal the 10 cm soil surface relative moisture in Shenmu City, with higher weights for temperature and precipitation in the model, reflecting the dominant role of temperature and precipitation in regional drought; drought conditions during the crop growing season in Shenmu City are generally at mild drought intensity, with an average occurrence frequency of 64.44%, and the ranking moderate drought > mild drought > severe drought > extreme drought, with both drought intensity and occurrence frequency exhibiting spatial differentiation characteristics of being higher in the northwest and lower in the southeast; from April to October, drought intensity generally develops from mild drought to severe drought, and finally disappears. Seasonally, spring drought in Shenmu City is severe, with moderate drought having the highest occurrence frequency. From 2001 to 2019, drought conditions in Shenmu City showed a slight alleviating trend, but drought conditions in the Hongjiannao Wetland intensified due to significant increases in annual mean temperature and annual evaporation.

ChinaRxiv 中X

Full Text

Remote Sensing Monitoring of Soil Drought Integrating GPM Precipitation Data

TAN Huizhi[1], YIN Qian[1], JI Liwen[1], LU Qian[2], LU Xiaoning[1], CUI Linlin[1], XIA Zhiye[1], XU Weixin[1], CHEN Jun[1]

[1]College of Resources and Environment, Chengdu University of Information Technology, Chengdu, Sichuan, China
[2]Shenmu Meteorological Bureau, Shenmu, Shaanxi, China

Abstract

Global warming has intensified drought trends, posing a severe threat to agricultural and pastoral production in the arid and semi-arid regions of northwestern China. Considering the typical Loess Plateau geomorphological characteristics of Shenmu City, Shaanxi Province, and the decisive role of precipitation on drought in areas with complex geomorphic backgrounds, this study applied high-precision Global Precipitation Measurement (GPM) data to establish a soil drought remote sensing monitoring model capable of revealing soil relative humidity. The results demonstrate that the comprehensive vegetation-temperature-precipitation soil drought remote sensing monitoring model built with GPM precipitation data can accurately reveal the relative humidity of the soil surface within 10 cm in Shenmu City. The model assigns relatively high weights to temperature and precipitation, reflecting their dominant role in regional drought. During the crop growing season, the overall drought intensity in Shenmu City is at the light drought level, with an average occurrence frequency of 64.44% (moderate drought > light drought > severe drought > extreme drought). Both drought intensity and occurrence frequency exhibit spatial differentiation characteristics of being higher in the northwest and lower in the southeast. The intra-annual drought intensity generally develops from light drought to severe drought, after which drought disappears. Seasonally, Shenmu City experiences severe spring drought, with moderate drought showing the highest occurrence frequency. Over the 19-year study period, the drought situation in Shenmu City showed a slight alleviating trend, but the drought conditions in the Hongjiannao wetland intensified due to significantly rising annual average temperature and evaporation.

Keywords: global precipitation measurement; moderate-resolution imaging spectroradiometer; drought; relative soil humidity; Shenmu City

1. Study Area and Data

1.1 Study Area Overview

Shenmu City is located in Yulin City, Shaanxi Province, situated in the middle reaches of the Yellow River, with geographical coordinates of

109°40 6.97 ~110°55 8.33 E, 38°12 29.05 ~39°27 16.70 N. The city extends approximately 140 km from north to south and 110 km from east to west, covering a total area of 7,670 km^2, making it the largest county-level city in Shaanxi Province. The terrain is characterized by higher elevations in the northwest and lower in the southeast, with altitudes ranging from 1,150 m to 1,425 m. The region features a pronounced continental climate with dramatic temperature variations, dry conditions, and frequent disasters. Precipitation decreases from south to north with large inter-annual variability, averaging 392.5 mm annually and concentrating between June and September. The area experiences prevailing westerly and northwesterly winds, with maximum wind speeds exceeding 25 $m \cdot s^{-1}$.

1.2 Data Sources and Preprocessing

1.2.1 Data Sources Remote sensing data included Land Surface Temperature (LST) and Normalized Difference Vegetation Index (NDVI) from the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard NASA' s Terra satellite, obtained from the National Aeronautics and Space Administration (https://www.nasa.gov). The study utilized daily GPM_{IMERG} precipitation product datasets at 0.1°$×0.1°spatialresolution, 8−daycompositeMOD11A2LSTproductdatasetsat1km× daycompositeMOD13A2NDVIproductdatasetsat1km×$1 km spatial resolution, all covering the crop growing season (April-October) from 2001 to 2019.

Soil relative humidity data were obtained from the Shenmu National Basic Meteorological Station (38°49 N, 110°28 E), including hourly average relative humidity data for the 10 cm and 20 cm soil layers. Meteorological station precipitation data from one national station and 20 regional stations in Shenmu City were selected for validating GPM data accuracy.

Soil texture spatial distribution data were obtained from the Resource and Environmental Science and Data Center of the Chinese Academy of Sciences (http://www.resdc.cn). Based on this data, Shenmu City' s soil texture composition was determined to be primarily sandy loam, with clay accounting for 65.60% and silt for 22.55%.

1.2.2 Data Preprocessing Due to different units among various factors, standardized processing was required. Pixels with cloud, water, or snow cover were assigned a value of 1 as these areas cannot experience drought. Using the GPM data sampling frequency as the baseline, maximum value normalization was applied to NDVI and LST data, while minimum value normalization was applied to precipitation data. Temporally, all data were resampled to 8-day intervals using maximum value composition. Spatially, the 0.1°$×$0.1° GPM data were resampled to 1 km resolution using bilinear interpolation to match the MODIS data, achieving unified spatiotemporal resolution.

1.2.3 Data Processing To validate GPM data accuracy, effective daily measured precipitation data from the Shenmu national station and 20 regional stations (totaling 6,354 days) were correlated with corresponding GPM_{IMERG} data (Table 1). All stations passed significance tests at the 0.01 level, demonstrating the reliability and feasibility of using GPM data for drought monitoring in place of limited meteorological station data.

2. Establishment of the Soil Drought Remote Sensing Monitoring Model

2.1 Determination of Model Dependent Variables

Correlation analysis was performed between soil moisture data from the Shenmu monitoring station and MODIS-derived indices. Results showed that 10 cm soil relative humidity was significantly correlated with VCI, TCI, and PCI at the 0.01 level, while 20 cm soil relative humidity was only significantly correlated with PCI (Table 3). This aligns with research conclusions from similar regions, confirming that 10 cm soil relative humidity should serve as the dependent variable for the soil drought remote sensing monitoring model. Additionally, Shenmu City' s sandy soil texture has poor water retention, with significant moisture changes occurring in the surface layer, making it more susceptible to drought. This further supports the scientific validity of using 10 cm soil relative humidity as the model dependent variable.

2.2 Model Establishment and Validation

Using 10 cm soil relative humidity data from 14 periods (randomly selected from 2001-2019, with 11 periods for modeling and 3 for validation), a Soil Moisture Monitoring Index (SMMI) was constructed through multiple linear regression integrating vegetation, temperature, and precipitation factors:

$$SMMI = 0.384VCI + 0.769TCI + 0.640PCI - 0.022$$

The model indicates that smaller SMMI values correspond to more severe drought conditions. Temperature and precipitation carry the highest weights, demonstrating their dominant control over soil drought in this region.

Validation using data from three periods showed a correlation coefficient of 0.774 (significant at the 0.01 level) between simulated and measured 10 cm soil relative humidity values, with a root mean square error (RMSE) of 0.067, confirming the model' s reliability (Figure 2).

Drought severity was classified based on soil relative humidity values: no drought (0.55-1.00), light drought (0.45-0.55), moderate drought (0.35-0.45), severe drought (0.25-0.35), and extreme drought (0.00-0.25) (Table 4).

3. Spatiotemporal Evolution of Drought During the Crop Growing Season

3.1 Spatial and Temporal Distribution of Drought Intensity

3.1.1 Spatial Distribution of Drought Intensity Based on the drought classification standard for sandy soil texture, the multi-year average spatial distribution of soil drought intensity during the crop growing season (April-October) in Shenmu City was derived (Figure 3). The city exhibits an overall light drought status, with drought intensity clearly stronger in the northwest than in the southeast. The area proportion of different drought grades shows light drought as the largest (75.15%), followed by moderate drought (18.78%), and no drought as the smallest (6.07%). Hongjiannao, the largest desert freshwater lake in China, maintains a no-drought status, accounting for over 0.56% of Shenmu' s total area. The eastern towns of Langanbao, Shenmu, Huashiya, and Hejiachuan also experience no-drought conditions. Most western regions fall between 0.45–0.55, indicating light drought status, while central areas including Jinjie, Dabaodang, and Erlintu towns show moderate drought (0.35–0.45). Overall, drought intensity in Shenmu City demonstrates a decreasing trend from northwest to southeast (Figure 3), consistent with research conclusions for Shaanxi Province.

This pattern occurs because the northwestern part belongs to the wind-sand beach area with sparse vegetation cover, relatively high surface temperatures, and strong northwest wind erosion that accelerates soil water loss, resulting in more severe drought conditions. As the wind moves southeastward, weakened wind speed, increased topographic relief enhancing orographic rainfall, higher vegetation coverage, and lower surface temperatures collectively slow soil water loss, creating a spatial gradient of increasing soil moisture from northwest to southeast.

3.1.2 Intra-Annual Variation of Drought Intensity Multi-year average intra-annual SMMI values during the crop growing season range from 0.255 to 0.979, with minimum values occurring in period 14 and maximum values in period 5 (Table 5). Drought intensity primarily manifests as no drought in period 1, moderate drought in periods 2–4, severe drought in period 5, and light drought in periods 6–14.

In mid-April (period 1), the region experiences light drought conditions covering 71.12% of the area, while moderate drought accounts for 27.42%. By late May to early June (period 5), drought conditions become most severe, with severe drought affecting 49.98% of the area, concentrated in Erlintu, Jinjie, Zhongji, Dabaodang, Sunjiacha, Daliuta, and parts of Shenmu and Gaojiabao towns. This spring drought intensification results from the weakening winter monsoon and reduced Pacific warm moisture flow.

As summer progresses, increased precipitation from the northward-moving southeast monsoon significantly alleviates drought conditions. Severe drought area proportion decreases from 49.98% to 0.66% by mid-July (period 7), disappearing entirely by late July (period 8). Moderate drought also diminishes substantially. Light drought and no-drought conditions become increasingly prevalent, with no-drought area expanding from 0.34% in mid-July to 24.18% by late September (period 13), affecting eastern and southern towns. From late August (period 10) onward, the region enters a no-drought dominant state that gradually expands northwestward. By late October (period 14), drought disappears completely.

3.2 Spatial and Temporal Distribution of Drought Frequency

3.2.1 Spatial Distribution of Drought Frequency From the perspective of drought occurrence frequency (considering light drought and above as drought events) (Figure 6), Shenmu City experiences an average drought frequency of 64.44% during the crop growing season, showing an increasing gradient from southeast to northwest that aligns with drought intensity patterns. This stability reflects the region's long-term drought characteristics and can guide targeted drought prevention.

Drought frequency is highest in Dabaodang town in the west (89.88%), followed by Erlintu (76.43%) and Jinjie (70.30%) towns, making these critical areas for drought prevention. Langanbao town shows the lowest frequency (24.03%), with Huashiya and Hejiachuan towns also experiencing relatively low frequencies (52.32% and 54.31% respectively).

Among different drought grades, moderate drought occurs most frequently (average 43.92%) with low geographic variation (CV = 19.63%), demonstrating its universal spatiotemporal presence and indicating that drought prevention measures should target moderate drought resistance levels. Light drought frequency shows a slightly north-high, south-low pattern with minimal geographic difference (CV = 13.72%). Extreme drought, though lowest in frequency (average 4.26%), exhibits the most significant geographic variation (CV = 60.86%), with high-frequency zones concentrated in Dabaodang (15.38%) and Jinjie (8.26%) towns.

3.2.2 Intra-Annual Variation of Drought Frequency Seasonal analysis reveals that spring drought (April–May) occurs most frequently (average 54.20%), followed by summer (22.64%) and autumn (16.31%) (Figure 8). Spring drought is dominated by moderate drought (43.92% frequency), with severe and light drought frequencies both reaching 24.20%. Despite low vegetation coverage (NDVI = 0.28) and minimal precipitation ($0.75\ \mathrm{mm \cdot d^{-1}}$), high temperatures (31.98°C) create severe spring drought conditions.

Summer drought frequency decreases significantly due to abundant moisture from the southeast monsoon, though extreme drought frequency increases to 6.13% because vegetation response lags behind climate conditions. Autumn drought frequency is lowest, dominated by light drought (19.55%), as reduced precipitation is offset by decreasing temperatures and the legacy effect of summer vegetation growth.

3.3 Spatial and Temporal Trends of Drought Variation

3.3.1 Spatial Distribution of Drought Trends Using pixel-by-pixel linear regression analysis, the slope of SMMI variation from 2001 to 2019 was calculated to assess drought trends (Figure 10). Shenmu City shows an overall slight alleviating trend (slope range: -0.245 to 0.150, average: -0.012), consistent with research on the Loess Plateau. This trend results from slowly decreasing temperature, gradually increasing precipitation, and relatively significant vegetation growth (Figure 11), attributable to China' s Grain for Green program implemented since 1999.

However, 0.44% of the area, concentrated in Hongjiannao wetland in Erlintu town, shows a slight intensifying trend (slope > 0). Despite being a relatively humid area, Hongjiannao has experienced significantly increased annual average temperature and evaporation, leading to lake area shrinkage and aggravated drought conditions.

3.3.2 Intra-Annual Variation of Drought Trends At the seasonal scale, all seasons show slight but non-significant alleviating trends (Figure 12). Summer shows the strongest alleviating trend (slope = -0.015) due to significant precipitation increase and large surface temperature decrease. Spring and autumn show weaker trends (slope = -0.011 and -0.010 respectively).

4. Conclusions

This study, focusing on Shenmu City in Shaanxi Province with typical Loess Plateau geomorphological features and emphasizing precipitation' s decisive role in complex terrain, developed a soil drought remote sensing monitoring model integrating vegetation, temperature, and precipitation based on high-precision GPM radar precipitation products. The spatiotemporal evolution of drought during the crop growing season (April–October) from 2001 to 2019 was analyzed from perspectives of intensity, frequency, and trend. The main conclusions are:

1. The soil drought remote sensing monitoring model (SMMI = 0.384VCI + 0.769TCI + 0.640PCI - 0.022) effectively reflects soil relative humidity within 10 cm and represents the optimal model for revealing regional soil drought. The high weights of temperature and precipitation indicate their dominant control over regional drought conditions.

2. The multi-year average drought intensity during the crop growing season in Shenmu City falls into three categories: light drought, moderate drought, and no drought, with light drought being predominant. Drought intensity shows intra-annual variation characterized by intensification before late May (developing from light to severe drought) and continuous alle-

viation afterward (developing from severe drought to moderate, light, and no drought after mid-August). Seasonally, spring drought is severe with the highest frequency of moderate drought. Summer drought frequency decreases but extreme drought frequency increases. Autumn drought shows the lowest frequency, dominated by light drought.

3. The average drought occurrence frequency in Shenmu City is 64.44%, showing an increasing gradient from southeast to northwest. Different drought grades exhibit varying frequencies: moderate drought > light drought > severe drought > extreme drought. Although extreme drought has low frequency, its geographic variation is significant. Moderate drought has the highest frequency with minimal geographic variation.
4. Over the 19-year period, Shenmu City' s drought situation showed a slight alleviating trend, though the Hongjiannao wetland experienced intensified drought. At the seasonal scale, all seasons showed non-significant slight alleviating trends, with summer showing the strongest alleviation.

Acknowledgments

The meteorological station data and soil relative humidity data used in this study were provided by the Shenmu Meteorological Bureau of Shaanxi Province. We express our sincere gratitude for their support.

References

[1] Shi Benlin, Zhu Xinyu, Hu Yunchuan, et al. Spatial and temporal variations of drought index sensitive to global warming: the standardized precipitation evapotranspiration index[J]. Journal of Climate, 2010, 23(7): 1696-1718.

[2] Lin Yan, Gao Wei, Shi Jinping, et al. Remote sensing monitoring of drought based on MODIS and FY-2D satellite rainfall data[J]. Journal of Arid Land Resources and Environment, 2014, 28(12): 51-57.

[3] Lu Xiaoning, Zhang Jingyi, Wang Lingling, et al. Remote sensing monitoring of summer drought at monthly scale considering vegetation, temperature and precipitation in Sichuan Province[J]. Journal of Natural Resources, 2017, 32(7): 1145-1157.

[4] Chang Jianxia, Li Yunyun, Wang Yimin, et al. Copula based drought risk assessment combined with an integrated index in the Wei River Basin, China[J]. Journal of Hydrology, 2016, 540: 824-834.

[5] Cong D, Zhao S, Chen C, et al. Characterization of droughts during 2001-2014 based on remote sensing: A case study of Northeast China[J]. Ecological Informatics, 2017, 39: 56-67.

[6] Li Xiaolan, Lyu Xiang, Wang Xiaohong, et al. Biotic and abiotic stress responsive genes are stimulated to resist drought stress in purple wheat[J]. Journal

of Integrative Agriculture, 2020, 19(1): 37-45.

[7] Gao Ya, Suikang, Yong Bin. Evaluation of the GPM based IMERG and GSMAP precipitation estimates over the Sichuan region[J]. Acta Geographica Sinica, 2019, 74(7): 1305-1318.

[8] Chen Luyan. The Research Based on the MODIS Data of Soil Moisture in Yulin[D]. Xi' an: Chang' an University, 2015.

[9] Sun Bo, Deyu, Huang Yue, et al. Multi-scale analysis of drought and its driving factors in Sichuan[J]. Transactions of the Chinese Society of Agricultural Engineering, 2019, 35(9): 138-146.

[10] Lu Xiaoning, Zeng Qianjing, Chen Xi, et al. Consistency and comparison among remote sensing drought indices and SMAP soil moisture in Kazakhstan[J]. Arid Zone Research, 2020, 37(3): 663-670.

[11] Cheng Peikun, Hu Shougeng, Sun Tao, et al. Effect of grain for green project on vegetation regeneration in Shaanxi Province: Based on PCSE panel data model[J]. Arid Zone Research, 2018, 35(6): 1477-1486.

[12] Wang Tao, Yang Meihuan. Dynamic change of NDVI and its response to climate change and human activities in Yulin, Shaanxi Province, China[J]. Arid Zone Research, 2017, 34(5): 1133-1140.

[13] Tang Guoqiang, Ma Yingzhao, Di L, et al. Evaluation of GPM Day-1 IMERG and TMPA Version-7 legacy products over Mainland China at multiple spatiotemporal scales[J]. Journal of Hydrology, 2016, 533: 152-167.

[14] McKee T B, Doesken N J, Kleist J. The relationship of drought frequency and duration to time scales: Proceedings of vulnerability[M]. Cambridge: Cambridge University Press, 1993: 100-184.

[15] Huete A, Didan K, Miura T, et al. Overview of the radiometric and biophysical performance of the MODIS vegetation indices[J]. Remote Sensing of Environment, 2002, 83(1): 195-213.

[16] Sandholt I, Rasmussen K, Andersen J. A simple interpretation of the surface temperature/vegetation index space for assessment of surface moisture status[J]. Remote Sensing of Environment, 2002, 79(2): 213-224.

[17] Vicente-Serrano S M, Beguería S, López-Moreno J I. A multiscalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index[J]. Journal of Climate, 2010, 23(7): 1696-1718.

[18] Wang Xiaofei, Gao Maofang, et al. Drought monitoring in Qujing based on temperature vegetation drought index[J]. Chinese Agricultural Science Bulletin, 2020, 36(9): 37-45.

[19] Liu Yufeng, Yuan Zhihua, Feng Jianmin, et al. Dry-wet condition of Shaanxi Province in recent 56 years based on surface humidity index[J]. Arid Land Geography, 2016, 39(6): 1186-1196.

[20] Standardization Administration of the P. R. C. National Standard of the People's Republic of China: Agricultural Drought Grade Standard GB/T 32136-2015[S]. Beijing: China Standard Press, 2015.

[21] Yan Enping, Lin Hui, Dang Yongfeng, et al. The spatiotemporal changes of vegetation cover in Beijing-Tianjin sandstorm source control region during 2000-2012[J]. Acta Ecologica Sinica, 2014, 34(17): 5007-5020.

[22] Xu Liping. Influence and Reciprocal Effects of Vegetation Rehabilitation on Regional Climate in Loess Plateau[D]. Xi' an: Northwest A&F University, 2008.

[23] Deng Yuanjie, Hou Mengyang, Xie Yifan, et al. Impact of the grain for green project on the temporal and spatial evolution of ecosystem service value in northern Shaanxi[J]. Acta Ecologica Sinica, 2020, 40(18): 6597-6612.

[24] Hu Pengfei, Li Jing, Wang Dan, et al. Monitoring agricultural drought in the Loess Plateau using MODIS and TRMM data[J]. Arid Land Geography, 2019, 42(1): 172-179.

[25] Li Jing, Wang Lianxi, Shen Cheng, et al. Application and comparison of several drought monitoring models in northern Shaanxi[J]. Chinese Journal of Agrometeorology, 2014, 35(1): 97-102.

[26] Ou Tinghai, Qian Weihong. Vegetation variations along the monsoon boundary zone in East Asia[J]. Chinese Journal of Geophysics, 2006, 49(3): 698-705.

[27] Zhou Liantong, Huang Ronghui. Interdecadal variability of sensible heat in arid and semi-arid regions of Northwest China and its relation to summer precipitation in China[J]. Chinese Journal of Atmospheric Sciences, 2008, 32(6): 1276-1288.

[28] Wang Yuanyuan, Li Guicai, Guo Zheng, et al. Spatial-temporal analysis of monthly air temperature changes from 1979-2014 in the Three Gorges Dam region[J]. Journal of Remote Sensing, 2018, 22(3): 487-496.

[29] Li Shuangshuang, Kong Feng, Han Lu, et al. Spatiotemporal variability of extreme precipitation and influencing factors on the Loess Plateau in northern Shaanxi province[J]. Geographical Research, 2020, 39(1): 140-151.

[30] Wang Lina, Zhu Qingke, Weng Baisha, et al. Temporal and spatial distribution characteristics of drought in Loess Plateau from 1961 to 2012[J]. Water Resources and Hydropower Engineering, 2018, 49(2): 15-22.

[31] Wei Xindong, Song Linhan, Wang Shaini, et al. Spatial and temporal changes and its variation of cultivated land quality of counties and cities in Shaanxi on the west bank of the Yellow River[J]. Research of Soil and Water Conservation, 2021, 28(2): 326-334.

[32] Wang K, Li T, Wei J. Exploring drought conditions in the three river headwaters region from 2002 to 2011 using multiple drought indices[J]. Water,

2019, 11(2): 190. https://doi.org/10.3390/w11020190

[33] Zhuo Jing, Zhu Yannian, Wang Juan, et al. Spatio-temporal change of water area in Hongjiannao Lake and the effectiveness of protection measures[J]. Journal of Desert Research, 2019, 39(4): 195-203.

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