Analysis of Impact Characteristics of Environmental Conditions on Vegetation Drought Status in the Yellow River Basin (Postprint)

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Abstract

To clarify the spatial response of different vegetation drought indices to climate change in the Yellow River Basin, data from 2003-2022 including the Vegetation Condition Index (VCI), Vegetation Health Index (VHI), Temperature Vegetation Dryness Index (TVDI), precipitation, temperature, and evapotranspiration were selected. Combined with trend analysis, spatial path analysis, and Multilayer Perceptron (MLP) regression analysis, the spatiotemporal variation characteristics of three vegetation drought indices in the Yellow River Basin were investigated, revealing the direct, indirect, and comprehensive effects of climate factors on vegetation drought status in the basin. The results show that: (1) Within the 20-year period, VCI and VHI exhibited fluctuating upward trends, while TVDI showed no significant increasing or decreasing trend; spatially, demarcated by the temperate-warm temperate boundary, TVDI in the southeastern direction and VHI in the northwestern direction showed significant decreasing trends. (2) Precipitation had the strongest direct promoting effect on VCI, and temperature had the strongest direct promoting effect on TVDI; precipitation had the strongest indirect effect on TVDI, and temperature had the strongest indirect effect on VHI; TVDI was mainly inhibited by precipitation, while VCI and VHI were mainly promoted by temperature. (3) All three vegetation drought indices showed negative correlations with precipitation and temperature, and positive correlations with potential evapotranspiration; the main influencing factor for TVDI was potential evapotranspiration, while the most important influencing factor for VCI and VHI was temperature; VHI is most suitable for determining vegetation drought status in the Yellow River Basin. The research results can provide a theoretical basis for drought assessment and management in the Yellow River Basin.

Full Text

Analysis of the Influence of Environmental Conditions on Vegetation Drought Status in the Yellow River Basin

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Abstract

To clarify the spatial response characteristics of different vegetation drought indices to climate change in the Yellow River Basin, this study selected the Vegetation Condition Index (VCI), Vegetation Health Index (VHI), and Temperature Vegetation Dryness Index (TVDI) from 2003 to 2022, along with precipitation, temperature, and evapotranspiration data. Using trend analysis, spatial path analysis, and Multi-Layer Perceptron (MLP) regression analysis, we investigated the spatiotemporal variation characteristics of these three vegetation drought indices in the Yellow River Basin and revealed the direct, indirect, and comprehensive effects of climatic factors on vegetation drought status. The results show that: (1) VCI and VHI exhibited fluctuating upward trends, while TVDI showed no significant increasing or decreasing trend. Spatially, bounded by the temperate-warm temperate boundary, TVDI decreased significantly in the southeast direction, while VHI decreased in the northwest direction. (2) Precipitation had the strongest direct effect on VCI, while temperature had the strongest direct effect on TVDI. The indirect effects of precipitation on TVDI and temperature on VHI were also substantial. TVDI was primarily inhibited by precipitation, while temperature predominantly promoted VCI and VHI. (3) All three vegetation drought indices showed negative correlations with precipitation and temperature, and positive correlations with potential evapotranspiration. Potential evapotranspiration was the primary influencing factor for TVDI, while temperature was the main influencing factor for VCI and VHI. Among these indices, VHI is most suitable for assessing vegetation drought status in the Yellow River Basin. These findings provide a theoretical basis for drought assessment and management in the Yellow River Basin.

Keywords: Yellow River Basin; drought; path analysis; MLP regression analysis; vegetation drought index

1. Materials and Methods

1.1 Study Area The Yellow River originates from the Bayan Har Mountains in western China and is the second longest river in China. The Yellow River Basin (32°10 ~41°50 N, 95°53 ~119°05 E) is mostly located in arid and semi-arid regions, with elevations ranging from -6 to 6272 m. The multi-year average precipitation is approximately 440 mm, concentrated but unevenly distributed. Both precipitation and temperature decrease from south to north and from east to west. Most areas have abundant sunshine and high evapotranspiration, with multi-year average evaporation between 800-1800 mm, resulting in severe drought conditions. Coupled with global warming, reduced precipitation, and unreasonable water resource utilization, drought in the Yellow River Basin has intensified in recent years.

1.2 Data Sources and Preprocessing The Temperature Vegetation Dryness Index (TVDI) and Vegetation Condition Index (VCI) were calculated from the Normalized Difference Vegetation Index (NDVI) and Land Surface Temperature (LST) for drought monitoring, primarily to assess relative drought conditions across the entire region during specific periods in given years. The Vegetation Health Index (VHI) is the weighted average of VCI and Temperature Condition Index (TCI), where TCI reflects the ratio of current NDVI and LST values to historical maximum and minimum values for the same period, indicating drought impacts on vegetation index and canopy temperature. VHI has been widely used for drought monitoring and description.

We selected the 1 km resolution dataset for the Yellow River Basin (2003-2022) published by Xia Haoming at the National Cryosphere Desert Data Center (http://www.ncdc.ac.cn). This dataset was derived from MODIS Collection data via Google Earth Engine. Following the MODIS Product User Guide, we extracted pixels and categorized them into high-quality, marginal, and low-quality pixels based on pixel values. After masking calibrated pixels, we generated annual TVDI, VCI, and VHI datasets for the Yellow River Basin using high-quality pixels. Temperature, precipitation, and potential evapotranspiration data were obtained from Peng Shouzhang's datasets published on the Three Poles Environmental Big Data Platform (http://poles.tpdc.ac.cn/zh-hans/), including 1 km resolution monthly mean temperature, monthly precipitation, and monthly potential evapotranspiration datasets for China. The temperature and precipitation datasets were generated through spatial downscaling of WorldClim global climate datasets, while evapotranspiration data were calculated using the Penman-Monteith formula with monthly mean, minimum, and maximum temperature datasets. These datasets have been validated against meteorological observation data and widely applied. Annual mean temperature was calculated as the average of monthly values, while annual precipitation and evapotranspiration were summed from monthly values. All data were preprocessed to a uniform temporal resolution of 1 year and spatial resolution of 1 km$×$1 km, projected to the same coordinate system. The Yellow River Basin boundary data were obtained from the Yellow River Basin Soil and Water Conservation Ecological Environment Monitoring Center. Detailed information is provided in .

1.3 Analysis Methods 1.3.1 Trend Analysis

The Theil-Sen Median trend analysis was used to calculate the spatial distribution characteristics of trends for each drought index, with Mann-Kendall testing for significance. This method estimates trends using N pairs of data from n samples and is robust for discrete data and measurement errors. The formula is:

$$Q_i = \frac{x_j - x_k}{j - k} \quad (i = 1, 2, \ldots, N)$$

where x_j and x_k are the time series values of the j-th and k-th samples. After sorting N Q_i values, the median is calculated as:

$$\text{med} = \begin{cases} Q_{(N+1)/2} & \text{if } N \text{ is odd} \\ \frac{Q_{N/2}+Q_{(N/2)+1}}{2} & \text{if } N \text{ is even} \end{cases}$$

The sign of med indicates the trend direction, while its magnitude reflects steepness.

1.3.2 Path Analysis

Path analysis, developed by Sewall Wright, analyzes linear relationships between dependent and multiple independent variables by calculating path coefficients for different pathways. This method minimizes the influence of measurement units and variable variation to distinguish direct and indirect effects of multiple independent variables on a dependent variable. For spatial path analysis, the principle extends to converting all annual raster data pixel values within the study area into vector-based spatial data sequences. Using a target pixel as the center, neighboring pixels are converted into vector sequences, and the calculated path coefficients are assigned to the target pixel. This approach has been successfully applied in vegetation cover and hydrothermal analysis on the Loess Plateau and climate factor impacts on growing season vegetation in the middle and lower Yangtze River.

1.3.3 MLP Regression Analysis

The Multi-Layer Perceptron (MLP) is a feedforward supervised artificial neural network model consisting of input, hidden, and output layers. Neurons map input vectors to output vectors with full connections between layers. In regression analysis, backpropagation algorithms calculate gradients and propagate errors from the output layer back to the input layer to update network parameters. Multiple hidden layer neurons discover distributed feature representations of vectors, with connection weights adjusted iteratively through backpropagation to minimize training error. MLP’ s strong nonlinear mapping capability and high adaptability makes it suitable for analyzing complex nonlinear relationships between drought indices and meteorological parameters (precipitation, temperature, evapotranspiration). We extracted annual raster data means for the three meteorological parameters, converted them to time series, and randomly split them into training (80%), validation (10%), and test (10%) sets. The model used two hidden layers with sigmoid activation functions and a maximum training epoch of 1000, implemented on the MATLAB platform.

1.3.4 Accuracy Assessment

We used the coefficient of determination (R^2), Mean Absolute Error (MAE), and Root Mean Square Error (RMSE) to evaluate model accuracy:

$$MAE = \frac{1}{m}\sum_{i=1}^{m}|y_i - \hat{y}_i|$$

$$RMSE = \sqrt{\frac{1}{m}\sum_{i=1}^{m}(y_i - \hat{y}_i)^2}$$

where y_i is the observed value, $\hat{y}_i$ is the predicted value, and $\bar{y}$ is the mean of observed values.

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2. Results

2.1 Spatiotemporal Variation of Different Drought Indices To understand interannual distribution and variation trends of vegetation conditions in the Yellow River Basin, we calculated average values of different drought indices across years. The results show that VCI ranged from 0.58 to 0.66, with a weak decreasing trend of -0.003 $\cdot$ (10a)$^{-1}$. VHI fluctuated between 0.52 and 0.88, showing an increasing trend of 0.09 $\cdot$ (10a)$^{-1}$. TVDI ranged from 0.69 to 0.90, with a fluctuating upward trend at 0.05 $\cdot$ (10a)$^{-1}$. Notably, anomalies concentrated in 2018 due to favorable hydrothermal conditions, with annual mean temperature and monthly extremes 3-8°C higher than average.

Spatial trends were analyzed using Theil-Sen Median method from 2003-2022. TVDI showed the lowest variation, with slope values ranging from -0.025 to 0.019. Areas showing increasing trends accounted for 43.38% for VCI, 84.22% for VHI, and 67.54% for TVDI. High VCI and VHI values were concentrated in the southeastern basin, including the Weibei Loess Plateau gully region and Guanzhong Plain, which have temperate monsoon climates with relatively sufficient precipitation. The western and northwestern basin showed strong decreasing trends for VCI and increasing trends for TVDI, attributable to plateau-alpine and temperate continental climates in these arid and semi-arid regions. Overall, climate change in the Yellow River Basin over the past 20 years is demarcated by the temperate-warm temperate boundary, with vegetation health and moisture content decreasing in semi-humid areas while drought intensifies in semi-arid areas.

2.2 Spatial Path Analysis Between Drought Indices and Environmental Conditions Direct path coefficients between drought indices and precipitation/temperature reveal that precipitation has the strongest direct effect on VCI, while temperature has the strongest direct effect on TVDI. The direct path coefficients of temperature on VHI show a desert grassland center decreasing outward. Precipitation and temperature directly and indirectly affect vegetation growth and transpiration. Indirect path coefficients show that precipitation has the strongest promoting effect on TVDI and weakest inhibiting effect on VHI. Spatially, direct path coefficient distributions for precipitation and temperature complement each other, indicating that increased precipitation or decreased temperature both promote VCI and VHI trends.

For TVDI, precipitation shows negative direct path coefficients while temperature shows positive coefficients. The positive direct path control area for precipitation and temperature on VCI/VHI accounts for 57.29% and 52.96% respectively, centered around Yanshan-Taihang Mountains and central Gansu. Indirect path coefficients are generally opposite to direct coefficients, with absolute differences of 34.75%-92.19%. The indirect effects are particularly evident in the Loess Plateau agricultural and grassland ecological zone at the Qinghai border and the Fenwei Basin agricultural ecological zone in southwestern Shaanxi, consistent with findings that vegetation in high-population and agriculturally developed areas is strongly controlled by natural precipitation and temperature.

2.3 Regression Analysis Between Drought Indices and Environmental Conditions Based on path analysis, we supplemented potential evapotranspiration data in MLP regression to better explain drought index variation. Correlation analysis shows all vegetation drought indices are positively correlated with potential evapotranspiration and negatively correlated with precipitation and temperature. For TVDI, potential evapotranspiration is the primary influencing factor with feature importance of 0.95. For VCI and VHI, temperature is the main factor with importance values of 0.91 and 0.88 respectively. The MLP model achieved highest regression accuracy for VHI ($R^2 = 0.95$) and lowest for TVDI ($R^2 = 0.83$), indicating VHI provides the most accurate monitoring data for drought assessment in the Yellow River Basin.

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3. Discussion

Although numerous studies have examined drought and its indicators, most have specific applicability conditions due to drought' s complexity and broad societal impacts. VCI is easily affected by background conditions and cannot fully reflect vegetation status. TVDI is suitable for assessing vegetation water and temperature stress, while VHI is mainly used for monitoring agricultural drought in heterogeneous areas. The Yellow River Basin spans vast areas with insufficient water resources, predominantly arid and semi-arid climates where vegetation growth is strongly affected by drought, directly influencing soil erosion severity. Selecting appropriate vegetation drought indices is crucial for drought monitoring, assessment, and soil conservation.

Our findings show VCI and VHI decreased significantly in the northwestern basin, consistent with intensified drought in all seasons except winter. Spatially, as elevation decreases from west to east, precipitation becomes the controlling factor for vegetation growth, with water deficiency potentially causing negative vegetation responses to temperature. This is reflected in negative direct path coefficients between precipitation and TVDI in the middle and lower reaches, decreasing toward the estuary. Temperature, closely related to photosynthetic activity, is a key climate factor affecting vegetation drought, with its influence more pronounced in arid and semi-arid regions where high temperatures increase evapotranspiration and water limitation.

The comprehensive path coefficients (direct + indirect) show precipitation' s inhibiting effect on TVDI and temperature's inhibiting effect on VHI, consistent with MLP regression results. However, precipitation and temperature affect vegetation differently across growth stages, with stronger effects during early and mid-seasons than late season. Data limitations prevented separate analysis of growing vs. natural seasons. Additionally, factors like irrigation, cultivation, plant diseases, and pests were not included, limiting more detailed mechanism analysis.

4. Conclusions

This study selected TVDI, VCI, and VHI to assess vegetation drought status in the Yellow River Basin, analyzing their spatiotemporal patterns and the effects of temperature, precipitation, and evapotranspiration using path analysis and MLP regression. The main conclusions are:

1. **Temporal trends:** VCI and VHI showed fluctuating upward trends from 2003–2022, while TVDI remained stable. Spatially, bounded by the temperate-warm temperate boundary, TVDI decreased significantly in the southeast and VHI decreased in the northwest.
2. **Direct and indirect effects:** Precipitation had the strongest direct effect on VCI, while temperature had the strongest direct effect on TVDI. Precipitation' s indirect effect on TVDI and temperature' s indirect effect on VHI were also substantial. TVDI was primarily inhibited by precipitation, while temperature predominantly promoted VCI and VHI.
3. **Comprehensive effects and model performance:** All three indices were negatively correlated with precipitation and temperature, and positively correlated with potential evapotranspiration. Potential evapotranspiration was the main factor for TVDI, while temperature was primary for VCI and VHI. The MLP model achieved highest accuracy for VHI

($R^2 = 0.95$), making it the most suitable index for drought assessment in the Yellow River Basin.

These results provide theoretical references for drought assessment and management in the Yellow River Basin.

References

[1] Fei, Wang Zongmin, Yang Haibo, et al. Study of the temporal and spatial patterns of drought in the Yellow River Basin[J]. Scientia Sinica (Terrae), 2018, 48(9): 1169-1183.

[2] Qian Zhengan, Wu Tongwen, Song Minhong, et al. Arid disaster and advances in arid climate researches over northwest China[J]. Advances in Earth Science, 2001, 16(1): 28-38.

[3] Zhang Qiang, Zhang Liang, Cui Xiancheng, et al. Progresses and challenges in drought assessment and monitoring[J]. Advances in Earth Science, 2011, 26(7): 763-778.

[4] Chen Shihao, Men Baohui, Pang Jinfeng, et al. Temporal and spatial evolution of reconstructed non-stationary meteorological drought in the Yellow River Basin using integrated methods[J/OL]. Journal of Hydroelectric Engineering: 1-12 [2024-03-17].

[5] Zhang Qiang, Yao Yubi, Li Yaohui, et al. Progress and prospect on the study of causes and variation regularity of droughts in China[J]. Acta Meteorologica Sinica, 2020, 78(3): 500-521.

[6] Kogan F, Sullivan J. Development of global drought watch system using NOAA/AVHRR data[J]. Advances in Space Research, 1993, 13(5): 219-222.

[7] Li Weijiao, Wang Yunpeng. An analysis of the spatial-temporal characteristics of drought in Guangdong based on vegetation condition index from 2003 to 2017[J]. Journal of South China Normal University (Natural Science Edition), 2020, 52(3): 85-91.

[8] Gao Bingli, Gong Jie, Li Yan, et al. Analysis of multi-scalar characteristics of dry and wet conditions in the Yellow River Basin based on SPEI[J]. Arid Zone Research, 2022, 39(3): 723-733.

[9] American Meteorological Society. Meteorological drought policy statement[J]. Bulletin of American Meteorological Society, 1997, 78: 847-849.

[10] Wang Jinjie, Chen Hao, Zhang Ying, et al. Spatial and temporal analysis of agricultural drought in Jiangsu Province from 2001 to 2018 based on vegetation health index[J]. Jiangsu Agricultural Sciences, 2020, 48(6): 223-231.

[11] Zhang Leyuan, Wang Yi, Chen Yaning. Study on drought evolution characteristics and teleconnection driving forces based on vegetation condition index

in China[J]. Arid Zone Research, 2020, 37(2): 331-340.

[12] Kogan Felix N. Operational space technology for global vegetation assessment[J]. Bulletin of the American Meteorological Society, 2001, 82(9): 1949-1964.

[13] Sandholt Inge, Rasmussen Kjeld, Andersen Jens. A simple interpretation of the surface temperature/vegetation index space for assessment of surface moisture status[J]. Remote Sensing of Environment, 2002, 79(2-3): 213-224.

[14] Mu Lingli, Wu Bingfang, Yan Nana, et al. Validation of agricultural drought indices and their uncertainty analysis[J]. Bulletin of Soil and Water Conservation, 2007, 27(2): 119-122.

[15] Yin Guoying, Zhang Hongyan, Zhang Liangpei. Remote sensing monitoring of agricultural drought and vegetation sensitivity analysis in the middle and lower reaches of the Yangtze River from 2001 to 2019[J]. Geomatics and Information Science of Wuhan University, 2022, 47(8): 1245-1256, 1270.

[16] Xiang Daxiang, Jiang Ying, Chen Zhe, et al. Spatial-temporal characteristics of historical drought in the middle and lower reaches of Yangtze River based on standardized precipitation index and vegetation health index[J]. Journal of Changjiang River Scientific Research Institute, 2024, 41(3): 153-159, 165.

[17] Li Xinyao, Yang Lianan, Nie Hongmei, et al. Assessment of temporal and spatial dynamics of agricultural drought in Shaanxi Province based on vegetation condition index[J]. Chinese Journal of Ecology, 2018, 37(4): 1172-1180.

[18] Qiao Longxin, Zheng Zelin, Ma Xiaoyan, et al. A dataset of monthly VCI and TCI drought indices at a resolution of 1 km in the Yellow River Basin (2003-2021)[J]. China Scientific Data, 2023, 8(2): 223-233.

[19] Zhai Panmao, Zou Xukai. Changes in temperature and precipitation and their impacts on drought in China during 1951-2003[J]. Climate Change Research, 2005, 1(1): 16-18.

[20] Xu Mingli, Wang Fei, Xu Fei, et al. Study on drought evolution characteristics and teleconnection driving forces based on vegetation condition index in China[J]. Water Resources and Power, 2024, 42(4): 20-24, 19.

[21] Xia Haoming. A dataset of annual TCI, VCI, VHI and TVDI with the resolution of 1 km in the Yellow River Basin (2003-2022)[DB/OL]. National Cryosphere Desert Data Center, 2023.

[22] Sha Yintao, Liu Yi, Zhao Xiaoyan, et al. A dataset of annual TCI, VCI, VHI and TVDI with the resolution of 1 km in the Yellow River Basin (2003-2022)[J]. China Scientific Data, 2024, 9(2): 166-180.

[23] Peng Shouzhang. 1 km resolution monthly mean temperature dataset for China (1901-2021)[DB/OL]. A Big Earth Data Platform for Three Poles, 2019.

[24] Zhao Xiaoyan, Xia Haoming, Liu Baoying, et al. Spatiotemporal comparison of drought in Shaanxi-Gansu-Ningxia from 2003 to 2020 using various drought indices in Google Earth Engine[J]. Remote Sensing, 2022, 14(7): 1570.

[25] Tang Lixia. Effects of Landuse/Climate Variability on the Runoff and Sediment in Qingshuihe Watershed on the Loess Plateau, West Shanxi Province, China[D]. Beijing: Beijing Forestry University, 2009.

[26] Basic boundary data set of soil and water conservation in the Yellow River Basin[DB/OL]. National Cryosphere Desert Data Center, 2018.

[27] Zhang Shihu, Wang Yifeng, Hou Qinzheng, et al. Spatial and temporal characteristics of aridity index and association with AO and ENSO in Qinghai Province[J]. Pratacultural Science, 2015, 32(12): 1980-1987.

[28] Liu Qionghuan, Wang Xiuhong, Zhang Yili, et al. Vegetation degradation and its driving factors in the farming-pastoral ecotone over the countries along Belt and Road Initiative[J]. Sustainability, 2019, 11(6): 1590.

[29] Liu Junwen, Xie Shaofeng, Zhong Yanqin, et al. A multi-factor PWV prediction model based on MLP neural network for southern China[J]. China Sciencepaper, 2024, 19(1): 99-107, 122.

[30] Yao Yubi, Zhang Cunjie, Deng Zhenyong, et al. Overview of meteorological and agricultural drought indices[J]. Agricultural Research in the Arid Areas, 2007, 25(1): 185-189, 211.

[31] Zhang Qiang, Gao Ge. The spatial-temporal features of drought and flood disasters in the past 50 years and monitoring and warning services in China[J]. Science & Technology Review, 2004(7): 21-24.

[32] Yang Zekang, Tian Jia, Li Wanyuan, et al. Spatio-temporal pattern and evolution trend of ecological environment quality in the Yellow River Basin[J]. Acta Ecologica Sinica, 2021, 41(19): 7627-7636.

[33] Li Yunyun, Chang Jianxia, Fan Jingjing, et al. Agricultural drought evolution characteristics and driving mechanisms in the Yellow River Basin under climate and land use changes[J]. Transactions of the Chinese Society of Agricultural Engineering, 2021, 37(19): 84-93.

[34] Chen Lingyi, Zhu Xiufang, Tang Yijuan, et al. Time lag effect and influencing factors of meteorological and hydrological drought in the Yellow River Basin[J]. Scientia Geographica Sinica, 2023, 43(10): 1861-1868.

[35] Sidor Cristian Gheorghe, Popa Ionel, Vlad Radu, et al. Different ring responses of Norway spruce to air temperature across an altitudinal gradient in the Eastern Carpathians (Romania)[J]. Trees, 2015, 29(4): 985-997.

[36] Shi Shangyu, Yu Jingjie, Wang Fei, et al. Quantitative contributions of climate change and human activities to vegetation changes over multiple time scales on the Loess Plateau[J]. Science of the Total Environment, 2021, 755: 142419.

[37] Zhang Xiumei, Ma Bo, Zhang Yijie. Importance analysis of vegetation change factors in East Africa based on machine learning[J]. Bulletin of Soil and Water Conservation, 2023, 43(6): 227-236.

[38] Guo Zhongping. Quantitative Characters Genetic Analysis[M]. Beijing: Beijing Normal University Publishing House, 1986.

[39] Xie Shudi, Mo Xingguo, Hu Shi, et al. Responses of vegetation greenness to temperature and precipitation in the Three North Shelter Forest Program[J]. Geographical Research, 2020, 39(1): 152-165.

[40] Hu Bo, Chen Lihua. Characteristics of soil moisture and path analysis of influencing factors on different forest lands on the Loess Plateau[J]. Science of Soil and Water Conservation, 2021, 19(1): 79-86.

[41] Gong Jie, Gao Bingli, Li Yan, et al. Spatiotemporal variation of climate dry-wet condition and its potential trend in the Yellow River Basin from 1960 to 2020[J]. Chinese Journal of Agrometeorology, 2022, 43(3): 165-176.

[42] Wang Xiong, Zhang Chong, Li Qiang. Path analysis between vegetation coverage and climate factors in the Loess Plateau[J]. Acta Ecologica Sinica, 2023, 43(2): 719-730.

[43] Wang Fei, Wang Zongming, Yang Haibo, et al. Copula-based drought analysis using Standardized Precipitation Evapotranspiration Index: A case study in the Yellow River Basin, China[J]. Water, 2019, 11(6): 1298.

[44] Xu Yong, Pan Yuchun, Zou Bin, et al. Quantitative assessment of the impact of climate change on the growing season of vegetation gross primary productivity in the middle and lower reaches of the Yangtze River[J]. Environmental Science, 2024, 45(3): 1615-1628.

[45] Liang Shouzhen, Wang Meng, Han Dongrui, et al. Analysis of relationship between temperature vegetation dryness index and soil moisture at multiple temporal scales and drought monitoring[J]. Research of Soil and Water Conservation, 2024, 31(2): 149-157.

[46] Jiang Shanhu, Ren Mingming, Zhang Erzi, et al. Study on evolution characteristics of dry season runoff using a non-stationary GEV model in Source Region of the Yellow River[J]. Journal of Hohai University (Natural Sciences), 2023, 51(2): 1-7, 63.

[47] Zhang Zhiqiang, Liu Huan, Zuo Qiting, et al. Spatiotemporal change of fractional vegetation cover in the Yellow River Basin during 2000-2019[J]. Resources Science, 2021, 43(4): 849-858.

[48] Xue Lianqing, Wang Wenzhuang, Liu Yuanhong, et al. Response of gross primary productivity of vegetation to persistent drought-induced water deficit in the Yellow River Basin[J]. Water Resources Protection, 2024, 40(3): 44-51.

[49] Yuan Wenping, Zhou Guangsheng. Theoretical study and research prospect on drought indices[J]. Advances in Earth Science, 2004, 19(6): 982-991.

[50] Senyanzobe J M V, Mulei Josephine M, Bizuru Elias, et al. Impact of Pteridium aquilinum on vegetation in Nyungwe Forest, Rwanda[J]. Heliyon, 2020, 6(9): e04806.

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