Postprint: Analysis of Vegetation Dynamics and Hydrothermal Combination Impacts in the Turpan Basin from 2001-2017 Based on MODIS Data

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Abstract

Climate change and its impacts on vegetation in the arid regions of northwestern China have long been a subject of considerable concern. Taking the topographically unique Turpan Basin as the study area, this study investigates vegetation changes and their relationship with hydrothermal combination characteristics in the region from 2001 to 2017, using observed meteorological station data, reanalysis meteorological grid data, and MODIS satellite remote sensing vegetation indices, employing methods such as trend testing, linear regression, and partial correlation analysis. The results show that: (1) Precipitation in the Turpan Basin showed no significant change overall, but the northern mountainous areas experienced relatively large precipitation increases; air temperature showed a significant upward trend overall, particularly with greater warming in the central region of the basin floor. (2) The vegetation index (NDVI) for the entire region showed a highly significant increasing trend, with larger NDVI growth rates in the mountainous areas and central region. (3) Influenced by moisture sources and sunshine duration, NDVI values are highest at elevations of approximately 3,000 m in the mountainous areas surrounding the Turpan Basin, and the slope aspect with the best vegetation in the mountains is the northwest slope. (4) The hydrothermal combination in the Turpan Basin is complex; moisture conditions are the primary limiting factor for vegetation growth in most areas, and precipitation shows a good positive correlation with NDVI. In mountainous and desert areas, increased heat is not conducive to vegetation growth, but in the central region, influenced by groundwater and human activities, water supply is relatively stable, and increased heat is beneficial to vegetation growth.

Full Text

Preamble

Analysis of Vegetation Changes and Hydrothermal Combination Effects in the Turpan Basin from 2001 to 2017 Based on MODIS Data

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Abstract

Climate change and its impacts on vegetation in the arid regions of northwest China have long been a focus of scientific attention. This study examines the Turpan Basin, a region with distinctive topographical features, using measured meteorological station data, reanalysis meteorological grid data, and satellite remote sensing vegetation indices. Through trend testing, linear regression, and partial correlation analysis, we investigate vegetation changes in the region from 2001 to 2017 and their relationship with hydrothermal combination characteristics. The results show that: (1) Overall precipitation in the Turpan Basin showed no significant change, but precipitation increased more substantially in the northern mountainous areas, while temperature exhibited a significant upward trend overall, particularly in the central bottom region of the basin. (2) The Normalized Difference Vegetation Index (NDVI) for the entire region showed a highly significant upward trend, with larger growth rates in both mountainous and central areas. (3) Influenced by moisture sources and sunshine duration, NDVI values peaked at approximately 3,000 m elevation in the surrounding mountains, with northwest-facing slopes showing the best vegetation conditions. (4) The hydrothermal combination in the Turpan Basin is complex; moisture conditions represent the primary limiting factor for vegetation growth in most areas, with precipitation showing a good positive correlation with NDVI. In mountainous and desert regions, increased heat is detrimental to vegetation growth, but in the central area, where groundwater and human activities provide relatively stable water supply, increased heat benefits vegetation growth.

Keywords: Hydrothermal Combination; Vegetation Change; Climate Change; NDVI; Terrain; MODIS

1.1 Study Area Overview

The Turpan Basin is located in eastern Xinjiang, deep in the interior of the continent, surrounded by mountains on three sides with a depressed central area, covering a total area of approximately 5.85×10^4 km^2. The highest elevation is Bogda Peak in the Tianshan Mountains at 5,445 m, while the lowest point is Ayding Lake in the central basin at -154 m, the lowest place in China in terms of elevation. Due to its distance from the ocean and blockage by high mountains, moisture from the eastern oceans can hardly reach the area; water vapor transport relies mainly on prevailing westerly winds. The basin's climate is arid. Its geomorphological structure exhibits obvious zonal characteristics: the outermost ring consists of mountains (elevation > 1,500 m) with intense physical weathering, serving as the main source of materials for the basin; the second ring is alluvial-proluvial gravel Gobi (elevation approximately 1,500 m) with coarse surface materials, severe surface water leakage, and deep groundwater that flows toward the oasis area in the basin; the central area is an alluvial-proluvial plain (elevation < 300 m) with flat terrain and groundwater depth mostly within 15 m, where areas with irrigation conditions become irrigated agricultural zones, and salt marshes exist at the lowest part of the basin bottom.

1.2 Data Sources

The data types and sources used in this analysis are shown in .

1.3 Research Methods

1) Mann-Kendall Trend Test Method (hereinafter referred to as MK test)

The non-parametric MK test was used to test for trends in data sequences. The null hypothesis (H_0) is that there is no monotonic trend. The test statistic Z is calculated as follows:

$$Z = \begin{cases} \frac{S-1}{\sqrt{\mathrm{Var}(S)}} & S > 0 \\ 0 & S = 0 \\ \frac{S+1}{\sqrt{\mathrm{Var}(S)}} & S < 0 \end{cases}$$

where x_j and x_i are data values at time points j and i in the time series. The Z value follows a standard normal distribution, and the probability p-value of the MK test can be obtained from the Z value. Setting the significance level α = 0.01, trend types are classified into 7 grades based on the sign of the Z value and the p-value size, as shown in .

2) Univariate Linear Regression

Univariate linear regression was used to analyze the linear change rate of NDVI and climate factors over time, i.e., $Y = aX + b$, where the independent variable X is time, the dependent variable Y is the vegetation index or climate factor to be analyzed, and the slope a represents the change rate of the analyzed factor over time.

3) Partial Correlation Analysis
Partial correlation analysis examines the linear correlation between two variables while controlling for the linear influence of other variables, using the partial correlation coefficient r to characterize the degree of correlation between two factors. This paper only considers three elements—NDVI, precipitation, and temperature—so only three-variable partial correlation analysis is used. The partial correlation coefficient $r_{xy\cdot z}$ between x and y after removing the influence of variable z is calculated as follows:

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

where r_{xy}, r_{xz}, and r_{yz} are the correlation coefficients between variables x, y, and z taken two at a time. The partial correlation coefficient ranges from -1 to 1, with larger absolute values indicating stronger correlation.

2.1 Climate Change in the Turpan Basin

The Turpan Basin has a multi-year average precipitation ranging between 20-400 mm, with relatively more precipitation concentrated in the northern and western Tianshan Mountains. The northern mountainous area can receive up to 400 mm, while the southwestern mountainous area receives about 300 mm; precipitation inside the basin is scarce (e.g., the multi-year average at Turpan Station is 15.8 mm) and decreases from northwest to southeast. The multi-year average temperature ranges between 7-16°C, with the highest temperatures in the central area (e.g., the multi-year average at Turpan City is 16.0°C), and temperature decreasing with elevation (e.g., the multi-year average at Dabancheng Station is 14.3°C). The monthly average temperature difference reaches 35°C, and the difference between extreme maximum and minimum temperatures is 50°C.

2.1.1 Precipitation Changes

Affected by the westerly jet stream and mountain uplift, the relatively rainy areas in the Turpan Basin are concentrated in the northern and western Tianshan Mountains. The basin has two national benchmark meteorological stations: Turpan Station and Dabancheng Station. Figure 2 shows the annual precipitation changes from 2001 to 2017. Turpan Station, representing the central area, shows a multi-year average precipitation of 14.8 mm since the 21st century, with annual precipitation fluctuating between 5-30 mm and a slight declining trend. Dabancheng Station, representing the mountainous area, shows a multi-year average precipitation of 77.1 mm for the corresponding period, with precipitation continuously decreasing in the early 21st century and slightly alleviating after the 2010s.

Figures 3a and 3b show the spatial distribution of annual precipitation trends and change rates in the Turpan Basin from 2001 to 2017 calculated using GLDAS-2.1 reanalysis data. The results indicate that overall, precipitation in the Turpan Basin shows no significant trend, but the northern and western mountainous areas show significant increases, with growth rates reaching 40 $mm \cdot a^{-1}$, and the increasing trend in the northern mountains is more significant. The southern desert area also shows a significant upward trend, but with a very small growth rate. The northwestern mountainous area shows a significant decreasing trend, while the central area shows no significant trend but with some precipitation reduction.

2.1.2 Temperature Changes

Figures 3c and 3d show the spatial distribution of annual average temperature trends and change rates. Most areas show an extremely significant warming trend, except for the northern mountainous area and western piedmont zone, which show slight warming trends. From the perspective of warming magnitude, most areas have a growth rate of 0.15–0.3°C $\cdot a^{-1}$, with the western mountainous area having a lower change rate of 0.07°C $\cdot a^{-1}$.

Figure 2 shows the annual average temperature changes at Turpan and Dabancheng stations from 2001 to 2017. The annual average temperature at Turpan Station shows a slight upward trend, with a multi-year average of 16.0°C, rising by 1.7°C compared to 2001, with particularly significant warming after 2005. The annual average temperature at Dabancheng Station remains basically stable, with a multi-year average of 14.3°C, and the annual average temperature in 2017 is roughly the same as in 2001.

2.2 Spatial Distribution and Interannual Variation Characteristics of Vegetation

The land cover type in the Turpan Basin is mainly bare land, with grassland in mountainous and piedmont areas and sporadic forests (Figure 4). Precipitation in the mountains infiltrates at the piedmont and converges to the central basin area in the form of groundwater, forming oases. Groundwater also provides the main recharge source for Ayding Lake. There are cultivated lands in the central oasis area, and a small amount of water bodies and wetlands are distributed in the Ayding Lake area.

The multi-year average NDVI distribution is shown in Figure 4b. NDVI in desert areas is generally below 0.05, while in the central oasis area, especially near the three cities (Turpan, Toksun, and Shanshan), the vegetation index is higher, around 0.3. The vegetation index in the northern mountains is around 0.2, slightly higher in the western mountains (about 0.25).

The NDVI trend and change rate from 2001 to 2017 are shown in Figure 5. Almost all regional NDVI values show extremely significant growth. The NDVI growth rate is largest in the northern mountains, about 0.005 a^{-1}, followed by the central oasis area, with the western mountainous piedmont zone also showing growth. This indicates that vegetation cover in the Turpan Basin is gradually improving overall.

Figure 6 shows the annual average NDVI changes for the whole region and the central region. The central region NDVI is higher than the whole region average. The whole region NDVI shows an overall upward trend from 2001 to 2017, with a growth rate of 0.00076 a^{-1}, with prominent growth after 2009. Combined with Figure 2, NDVI fluctuations show good consistency with precipitation changes at Dabancheng, indicating that mountainous precipitation changes have a strong relationship with regional vegetation conditions. The central region NDVI shows continuous upward fluctuation, with a growth rate of 0.00086 a^{-1}.

Further analysis was conducted using the pixel dichotomy model to calculate vegetation coverage. Based on the analysis, NDVI < 0.05 can be considered bare soil area. Therefore, the vegetation coverage fraction is calculated as:

$$\text{Vegetation Coverage} = \frac{\text{NDVI} - \text{NDVI}_{\text{soil}}}{\text{NDVI}_{\text{veg}} - \text{NDVI}_{\text{soil}}}$$

where $\text{NDVI}_{\text{soil}}$ takes the minimum NDVI value in the central region (about 0.05), and NDVI_{veg} takes the maximum NDVI value in the central region after synthesizing the July-August NDVI values (the month with maximum NDVI). Coverage > 0.6 is considered high coverage, and < 0.3 is low coverage.

Figure 7 shows the percentage changes of different vegetation coverage levels in the central Turpan Basin during summer. The central Turpan area is dominated by low vegetation coverage, but overall vegetation coverage is increasing year by year with fluctuations. The increase in low vegetation coverage percentage indicates a trend of desert-to-oasis transition in the mixed transition zone between desert and oasis, with vegetation conditions improving year by year. This mutual conversion between oasis, desert, and ecotone is also reflected in areas such as the Keriya River basin in the Tarim Basin of the Hotan region in Xinjiang.

2.3 Factors Influencing NDVI Spatiotemporal Changes

2.3.1 Relationship Between NDVI Spatial Distribution and Terrain Factors

NDVI spatiotemporal distribution mainly depends on hydrothermal conditions, which are greatly influenced by terrain factors such as elevation and slope aspect. Two rectangular sample areas spanning different elevation ranges were selected on the southern slope of the northern Tianshan Mountains and the eastern slope of the western Tianshan Mountains (42.5°–43.5°N, 89.5°–90.5°E and 42.5°–43.5°N, 88.5°–89.5°E, respectively) to analyze the relationship between NDVI and elevation and slope aspect.

Figure 8 shows the relationship between elevation and NDVI in July (the month with maximum NDVI) in the sample areas. For the northern Tianshan Mountains southern slope sample area, elevations below 1,500 m are oasis areas. Due to complex surface cover types (including farmland and desert), NDVI fluctuates greatly (approximately 0.05–0.35), with the peak (about 0.35) appearing at approximately 2,900 m elevation. Above 4,000 m, NDVI drops to around 0.05, with perennial snow cover. For the western Tianshan Mountains eastern slope, NDVI values are around 0.05 at 500 m elevation, reflecting desert surface cover. NDVI values gradually increase with elevation, peaking at about 0.35 around 3,100 m, then gradually decreasing, but still with some vegetation cover around 4,000 m. Although the two sample areas in the northern and western Tianshan Mountains have similar latitudes and basically the same solar radiation conditions, the western Tianshan Mountains have better vegetation conditions, reflecting that under the same heat conditions, the western Tianshan Mountains have slightly better moisture conditions due to the main moisture source being westerly circulation.

Further analysis of slope aspect and NDVI relationship was conducted in sample areas with slopes of 250 m × 250 m. Figure 9 shows NDVI values for different slope aspects. For the northern Tianshan Mountains, the northwest-facing slope (approximately 315°) has the best vegetation, followed by east and southeast-facing slopes, while the north-facing slope has the poorest vegetation. For the western Tianshan Mountains, north, northwest, and west-facing slopes have the best vegetation, while the southeast-facing slope (approximately 135°) is relatively poor. This shows that for both the northern and western Tianshan Mountains, the best vegetation conditions occur on northwest-facing slopes. The reason is that the west-facing slope has the best moisture conditions (as moisture sources mainly come from westerly circulation), while the semi-shaded northwest-facing slope meets vegetation' s sunlight needs while having relatively shorter direct sunlight duration and lower evapotranspiration than south-facing slopes. In other words, in the mountains surrounding the Turpan Basin, the northwest-facing slope represents the optimal combination of moisture and heat conditions for plant growth.

2.3.2 Partial Correlation Between NDVI and Climate Factors in Different Geomorphic Regions

Partial correlation analysis was conducted between the Turpan Basin' s June-August NDVI and concurrent climate factor series (including cumulative precipitation and average temperature). The spatial distribution of partial correlation coefficients is shown in Figure 10. The results show that summer average NDVI in the whole region has a certain positive correlation with precipitation, especially in the northern mountainous area above 3,000 m elevation and the piedmont Gobi (elevation 1,500–2,000 m), with correlation coefficients above 0.5. However, in the alluvial-proluvial plain zone in the central basin, the correlation between NDVI and precipitation is relatively weak because the water source comes not only from precipitation but also importantly from groundwater.

The partial correlation between NDVI and temperature shows obvious regional characteristics. In mountainous areas above 3,000 m and in the southeastern desert area, NDVI shows a general negative correlation with temperature, reflecting that when temperature increases, evapotranspiration increases, reducing plant-available water and thus showing a negative correlation between NDVI and temperature. However, in the central area below 1,000 m elevation, the correlation between NDVI and precipitation is weaker, while the positive correlation with temperature is strong, with correlation coefficients reaching above 0.5. The reason is that groundwater here provides a relatively stable water supply source. Under these conditions, appropriate increases in summer temperature are conducive to vegetation growth. Overall, due to different water storage conditions under different geomorphic conditions, vegetation growth response characteristics to temperature and precipitation changes also differ.

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3 Discussion on the Mechanism of Hydrothermal Combination Effects on Vegetation Spatiotemporal Changes

3.1 Influence of Natural Factors on Vegetation Spatiotemporal Changes

Vegetation change is controlled by climate change, particularly temperature and precipitation. Suitable hydrothermal combinations are important guarantees for vegetation growth, but the dominant factors affecting vegetation growth status differ under different dry-wet environments. Except for alpine regions, water resource availability is a common controlling factor for vegetation growth. Vegetation in arid regions is more sensitive to precipitation than temperature, while vegetation in humid regions is more sensitive to temperature than in arid regions. When affected by a single climate factor, vegetation growth is often suppressed to some extent. For example, in the arid northwestern region of China, precipitation or temperature is far below the regional average level, limiting vegetation growth. In temperate zones at 40°N where water is the main limiting factor, vegetation productivity in precipitation-rich areas usually shows a strong positive correlation with temperature, while in areas with decreasing precipitation year by year, drought intensifies and the negative correlation between NDVI and temperature becomes more significant. In northwestern China, precipitation is the main driving factor for vegetation cover change in arid regions, with NDVI generally showing a positive correlation with precipitation, while temperature increase accelerates surface evaporation, aggravates vegetation water loss, and inhibits vegetation growth. On the other hand, the response relationship of vegetation to precipitation and temperature changes to some extent with changes in precipitation or temperature. Increased heat accumulation often enhances vegetation growth sensitivity to precipitation.

Affected by diverse moisture sources and complex terrain combinations, hydrothermal conditions in Xinjiang are complex, and different vegetation cover types have different requirements for hydrothermal conditions, making the impact of hydrothermal combination conditions on vegetation more complex. Studies have found that in mountainous areas where forest is the main vegetation cover type, water is relatively abundant, and increased radiation and longer sunshine hours lead to temperature rise while also extending the vegetation growing season. In the oasis-desert ecotone where small shrubs and other salt-alkali tolerant vegetation are the main types, moisture conditions are the main factors affecting vegetation growth. The main influencing factors for vegetation growth differ in different seasons. Spring and autumn vegetation cover shows greater correlation with temperature than precipitation, while summer shows the opposite pattern. Geographical location differences lead to varying hydrothermal conditions, making vegetation responses to climate different. Studies have shown that northern Xinjiang has the best vegetation cover and is more sensitive to hydrothermal condition changes, while southern Xinjiang has poorer vegetation with obvious lag in response to hydrothermal condition changes, and temperature is the main limiting factor for vegetation growth.

As part of an arid region, the Turpan Basin has scarce precipitation overall, and moisture conditions are the limiting factor for vegetation growth. Therefore, precipitation is generally positively correlated with NDVI, meaning increased precipitation is beneficial to vegetation growth. However, the impact of heat conditions on vegetation growth is more complex. For most regions, increased radiation and longer sunshine hours lead to temperature rise, which increases evapotranspiration, aggravates water shortage, and is detrimental to vegetation growth. However, due to the special terrain, precipitation from the whole region almost all converges to the central area below 1,000 m elevation, forming abundant groundwater. Especially in oasis areas, human extraction of groundwater for irrigating farmland and orchards makes moisture conditions better in this region, so vegetation growth is less dependent on precipitation than surrounding areas, and temperature rise instead improves heat conditions and benefits vegetation growth. Hydrothermal combination differences are also reflected in slope aspects. In humid areas with good moisture conditions, sunny slopes usually have better vegetation growth than shady slopes due to sufficient sunlight.

However, in arid and semi-arid areas, sunny slopes have stronger evapotranspiration than shady slopes, which limits plant growth. For example, shaded (north-facing) or semi-shaded (east-facing) slopes in the Qilian Mountains have relatively shorter direct sunlight duration, smaller evapotranspiration, and less soil moisture stress, making them more suitable for vegetation growth. The terrain gap in the northwest corner of the Turpan Basin is the entrance for Atlantic water vapor brought by mid-latitude prevailing westerly winds. The east-west oriented northern Tianshan Mountains have relatively uniform moisture conditions on all slopes, so vegetation indices are higher on northwest and southeast-facing slopes with more suitable heat conditions. The western Tianshan Mountains are approximately north-south oriented, with large differences in moisture conditions among different slope aspects. As the windward slope, the northwest-facing slope has abundant moisture and suitable light, showing the highest vegetation index, while the leeward southeast-facing slope has poor moisture conditions and relatively longer light duration, which is not conducive to vegetation growth. This shows that the special terrain of the Turpan Basin —small area with large elevation differences, high on three sides and low in the center—makes the hydrothermal combination complex, and the relationships between vegetation and terrain and meteorological factors are also complex.

3.2 Influence of Human Activities on Vegetation Spatiotemporal Changes

Human agricultural activities in the central area have greatly impacted NDVI through hydrothermal combination redistribution. Figure 11 shows the interannual variation of summer NDVI and the planting area of major crops (cultivated land and orchard land) in the central area from 2001 to 2017. The changes in summer NDVI and major crop planting area are basically consistent. Affected by meteorological factors, in individual years (such as 2008), due to insufficient precipitation, low temperature, and poor heat conditions, NDVI changes are not synchronized. In reality, human activities have very limited ability to improve heat conditions but can regulate the temporal and spatial distribution of water to some extent, thereby changing regional hydrothermal combination relationships. For example, in 2006, precipitation in the central area was extremely low, but heat conditions were relatively favorable. Improvements in agricultural water conservancy facilities and the use of pesticides and fertilizers improved crop growth conditions, and the resulting impact on vegetation cover often exceeded that of meteorological elements such as precipitation. The central area of the Turpan Basin is located at the lowest part of the entire region. Although precipitation is extremely scarce, precipitation from surrounding mountainous areas converges here in the form of underground runoff. People meet crop water consumption needs by extracting groundwater, so the impact of precipitation fluctuations on vegetation growth is relatively weak. Vegetation growth is more affected by groundwater depth or external water input. Agricultural irrigation provides good moisture conditions for crops in the central area. When water supply is sufficient, heat conditions become the main factor affecting vegetation growth.

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4 Conclusions

This study focuses on changes in precipitation, temperature, and other climate factors in the Turpan Basin from 2001 to 2017, combined with the region' s special terrain (small area with large elevation differences, high on three sides and low in the center) and human activity impacts. It deeply analyzes the role of natural and human activity factors in hydrothermal combination distribution in arid regions, highlighting the particularity and complexity of hydrothermal combination relationships in small-scale areas of arid regions. The results show that:

1) Overall precipitation in the Turpan Basin showed no significant change, but precipitation increased more in the northern mountains. Temperature showed a significant upward trend overall, especially in the central bottom region of the basin.

2) The Normalized Difference Vegetation Index (NDVI) for the entire region showed a highly significant upward trend, with larger growth rates in mountainous and central areas.

3) Affected by moisture sources and sunshine duration, NDVI values peaked at approximately 3,000 m elevation in the surrounding mountains, with northwest-facing slopes showing the best vegetation conditions.

4) The hydrothermal combination in the Turpan Basin is complex. Although moisture conditions are the main limiting factor for vegetation growth in most areas, as indicated by the positive correlation between precipitation and NDVI, the effects of temperature increase on vegetation growth are complicated. In mountainous and desert areas, increased heat is detrimental to vegetation growth, but in the central area, where groundwater and human activities provide relatively stable water supply, increased heat benefits vegetation growth.

References

[1] SHI Yafeng, SHEN Yongping, HU Ruji. Preliminary study on signal, impact and foreground of climatic shift from warm-dry to warm-humid in Northwest China [J]. Journal of Glaciology and Geocryology, 2002, 24(3): 219-226.

[2] HE Jinyun, ZHANG Mingjun, WANG Peng, et al. New progress of the study on climate change in Xinjiang [J]. Arid Zone Research, 2011, 28(3): 499-508.

[3] Reziwanguli ・Maimaitiyiming, YANG Jianjun, LIU Yongqiang. Characteristics of changes in temperature and precipitation in Xinjiang in recent 54 years

[J]. Research of Soil and Water Conservation, 2016, 23(2): 128-133.

[4] CI Hui, ZHANG Qiang. Spatio-temporal patterns of NDVI variations and possible relations with climate changes in Xinjiang province [J]. Journal of Geoinformation Science, 2017, 19(5): 662-670.

[5] ZHANG R, OUYANG Z, XIE X, et al. Impact of climate change on vegetation growth in arid northwest of China from 1982 to 2011 [J]. Remote Sensing, 2016, 8(5): 364.

[6] DU Z Q, ZHAO J, PAN H H, et al. Responses of vegetation activity to the daytime and nighttime warming in northwest China [J]. Environmental Monitoring and Assessment, 2019, 191(12): 1100-1109.

[7] MA Yonggang, ZHANG Chi, Tiyip Tashpolat. Spatial-temporal change of vegetation phenology in arid zone of central Asia and Xinjiang, China [J]. Climate Change Research, 2014, 10(2): 95-102.

[8] ZHANG Siqi, CHEN Hui, SONG Minghua, et al. Spatial and temporal variation of fractional vegetation cover and its relationship with environmental factors in the Qaidam Basin during 2000–2015 [J]. Arid Land Geography, 2019, 42(5): 1124-1132.

[9] WANG Zhao, PENG Yan, QUAN Wenting, et al. Characteristic of plant phenology and its response to the hydrothermal conditions over the Qinling Mountains [J]. Arid Land Geography, 2019, 42(5): 1048-1058.

[10] WANG Yu, AN Shazhou, DONG Yiqiang, et al. Effects of slope aspect on the vegetation diversity of mountain steppe in the northern slope of Tianshan Mountain, Xinjiang [J]. Xinjiang Agricultural Sciences, 2018, 55(1): 156-163.

[11] YUE Hui, LIU Ying. Vegetation spatiotemporal variation and its driving factors of Shaanxi province in recent 15 years [J]. Arid Land Geography, 2019, 42(2): 314-323.

[12] WANG Keli, JIANG Hao, ZHAO Hongyan. Atmospheric water vapor transport from westerly and monsoon over the northwest China [J]. Advances in Water Science, 2005, 16(3): 432-438.

[13] LI Zhen, YAN Fuli, FAN Xiangtao. The variability of NDVI over northwest China and its relation to temperature and precipitation [J]. Journal of Remote Sensing, 2005, 9(3): 308-313.

[14] ZHANG Chong, REN Zhiyuan, WEI Zhenfeng. Vegetation responses to intra-annual hydrothermal conditions on the Loess Plateau [J]. Resources Science, 2013, 35(10): 2017-2023.

[15] PIAO S L, NAN H, HUNTINGFORD C, et al. Evidence for a weakening relationship between interannual temperature variability and northern vegetation activity [J]. Nature Communications, 2014, 5(1).

[16] DE BEURS K M, HENEBRY G M. Land surface phenology and temperature variation in the International Geosphere-Biosphere Program high-latitude transects [J]. Global Change Biology, 2005, 11(5): 779-790.

[17] FORKEL M, MIGLIAVACCA M, THONICKE K, et al. Codominant water control on global interannual variability and trends in land surface phenology and greenness [J]. Global Change Biology, 2015, 21(9): 3414-3435.

[18] DU Jiaqiang, JIAERHENG Ahati, ZHAO Chenxi. Dynamic changes in vegetation NDVI from 1982 to 2012 and its responses to climate change and human activities in Xinjiang, China [J]. Chinese Journal of Applied Ecology, 2015, 26(12): 3567-3578.

[19] YANG Guanghua, BAO Anming, CHEN Xi. Study of the vegetation cover change and its driving factors over Xinjiang during 1998–2007 [J]. Journal of Glaciology and Geocryology, 2009, 31(3): 436-445.

[20] XIN Zhongbao, XU Jiongxin, ZHENG Wei. Effects of climate change and human activities on vegetation cover on the Loess Plateau [J]. Scientia Sinica (Terrae), 2015, 26(12): 3567-3578.

[21] SUN Yanling, GUO Peng, YAN Xiaodong, et al. Dynamics of vegetation cover and its relationship with climate change and human activities in Inner Mongolia [J]. Journal of Natural Resources, 2010, 25(3): 407-414.

[22] DU J, HE B, PIATEK K B, et al. Interacting effects of temperature and precipitation on climatic sensitivity of spring vegetation green-up in arid mountains of China [J]. Agricultural and Forest Meteorology, 2019, 269-270: 71-77.

[23] JIN X, WAN L, ZHANG Y K, et al. Quantification of spatial distribution of vegetation in the Qilian Mountain area with MODIS NDVI [J]. International Journal of Remote Sensing, 2009, 30(21): 5757-5770.

[24] Mann H B. Non-parametric tests against trend [J]. Econometrica, 1945, 13(3): 245-259.

[25] Kendall M G. Rank Correlation Methods [M]. Griffin, London.

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