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Dry and Wet Changes and Vegetation Time-Delay Responses in Western China

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Abstract: Due to global warming and other climate changes, it is increasingly important to study the response of regional environmental changes and dynamic changes in vegetation to climate change. Based on meteorological data from the last 60 years, this paper calculates the humidity index of western China under a wide range of long time series in different regions and explores the cross-correlation effect between series by offering a comparison with NDVI data, to analyze the cross-correlation between wet and dry changes and changes in vegetation in western China on a spatial scale. The results show that the spatial distribution of the interdecadal humidity index is different between different regions in western China. For example, the semi-arid and the semi-humid zones of the Weihe River region exhibit significant changes, while the Xinjiang and Qinghai–Tibet regions show a trend of constant wetness, on the whole, and the Sichuan and Yunnan–Guizhou regions are relatively humid and the distribution of wetness and dryness is relatively stable. The distribution of high and low values of the humidity index is very obvious and consistent with that of the distribution of desert bare land and precipitation in western China. In common with the distribution in the humidity index, the maximum correlation number between the NDVI and the humidity index in the whole western region is also significantly different in spatial distribution. There is a positive correlation between the NDVI and the humidity index in 99% of the study area. However, the delay in response time of the NDVI to changes in the humidity index in each region is inconsistent. For example, changes in the NDVI lag changes in the humidity index in the Menggan region by generally either 2 months or 5 months, while in the Sichuan region the delay in response time is generally 3 months. The variation and trend in dry and wet areas are closely related to the geographical location, climate zone, and topographic terrain, which may be the reason for the differences in the distribution of vegetation types and the response time to dry and wet changes. There is significant interaction between the humidity index and the vegetation type or precipitation distribution in western China. The positive correlation between the NDVI and the humidity index means that the positive effect is more sensitive, and the response of grassland is the most sensitive in the ecosystem.

Keywords: climate change; dry and wet conditions; humidity index; time lag; western China

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1. Introduction

As global warming intensifies, global, and even regional, water cycle processes and cycles intensify, bringing heavier rainfall and flooding but, also, in many areas, more severe droughts. The Sixth Assessment Report of the IPCC warns that climate change has caused huge damage and increasingly irreversible loss in terrestrial, freshwater, coastal, and remote Marine ecosystems [1–5]. "The dry places are getting drier and the wet places are getting wetter". The frequency and severity of extreme events of rainfall and other weather phenomena have increased, further complicating the dry and wet conditions and vegetation conditions in eco-fragile areas, such as semi-arid and sub-humid areas [6–8].

Existing studies have shown that the change in future dry–wet patterns is mainly characterized by a significant decrease in the wet zone and a significant expansion of the dry–wet transition zone. With the intensification of future warming, the sensitivity of China's dry–wet pattern to climate change may be enhanced [9–13]. Yang [14] pointed out that, since the 1950s, the drought level in north and southwest China has increased significantly ($p < 0.05$), which is closely related to the significant climate warming in recent decades. Hu et al., pointed out that, due to the increase in precipitation and decrease in evapotranspiration in most parts of southern China and the northwestern parts of Xinjiang, the climate has become wet [15]. Two factors are considered in different directions; the first is based on global warming, while the second is based on the income and expenditure of the regional water cycle. The dry–wet distribution in southwest China is relatively stable, while the dry–wet distribution in the arid area of the northwest polar region is the least stable. The wetting trend in northwest Xinjiang, Inner Mongolia, and the area along the Great Wall is significantly increasing, and humid areas are also increasing in China [16–20]. Wang et al. [21] pointed out that the Qinghai–Tibet Plateau, as a whole, presents a drying trend from southeast to northwest, and the difference between north and south is obvious. The spatial pattern of an enhanced vegetation index in the plateau growing season is similar to that of wetness and dryness, and the boundary between the east and the west is distinct. However, this differs from the research results of Zhang et al. [22], who analyzed the overall improvement in vegetation in the Qinghai–Tibet Plateau over the past 25 years based on ecogeographic zoning, especially in the humid and semi-humid areas and some semi-arid areas in the northeast, mid-east, and southwest. The correlation between vegetation cover change and temperature in the growing season is consistent with that across the whole year.

Most studies use data on only a single regional or local element in western China to study the difference in regional dryness and wetness and the response of vegetation to climate change. There is a lack of integrated research on western China. This paper, based on the meteorological elements of the whole western region, as well as the indexes of dry and wet changes, cover changes, and vegetation types, provides references for the dry and wet changes and vegetation effects in the whole western region under climate change in a long time series, a large area, and on a spatial scale.

2. Data and Methods

2.1. Study Area

The research scope of this study is the western region of China, including the southwest and northwest. In the north, west, and south of the study area, the national boundary or demarcation mountains are taken as the boundary, while in the east, the eastern boundaries of Yunnan, Guizhou, Chongqing, Shaanxi, and other provincial administrative regions, represent the study area. Inner Mongolia includes Alxa League, Wuhai City, Bayannur City, and Ordos City, which are mainly concentrated in continental temperate desert climate areas in western Inner Mongolia. Based on the climatic zoning map of China compiled by the China National Meteorological Administration in 1978 and the precipitation distribution data in western China, the study regions were divided into seven regions: the Xinjiang region, the Qinghai–Tibet region, the Menggan region, the Weihe region, the Qinba region, the Sichuan region, and the Yunnan–Guizhou region through consolidation and statistics [23,24]. The division is shown in Figure 1.

The study area is located between 73–111° E and 21–49° N. The climate is mainly continental, typical of plateau mountains. The southeast includes a small area with a subtropical monsoon climate. Areas with a temperate continental climate are mainly to be found in northwest China and include areas with a temperate arid climate, an extremely arid climate, and a temperate continental semi-arid climate. This region is dry and rainless. The annual precipitation in most areas is less than 200 mm, and in some basin areas, this even drops to less than 50 mm. Areas with a plateau mountain climate are mainly to be found in the Qinghai–Tibet Plateau, with significant vertical climate change, abundant sunshine, rare precipitation, and small annual temperature differences. The subtropical monsoon climate is mainly to be found in the Sichuan Basin and the Yunnan–Guizhou Plateau. The Sichuan Basin is low-lying and flat with widespread red rocks. Precipitation is distributed unevenly throughout the year and is mainly in summer. The Yunnan–Guizhou Plateau has a distinct climate, with distinct dry and wet seasons and typical karst landforms. The overall climate types in the western region are complex and diverse, and natural disasters occur frequently. The vegetation distribution includes desert steppe, desert, Gobi dunes, oasis, grassland fir forests, etc. The growth and distribution of surface vegetation are significantly affected by climate, as well as other photothermal factors. In recent years, with the aggravation of global warming and the influence of human factors, some studies show that there is a trend of warming and humidification in western China, but desertification and soil erosion still exist and are serious issues.

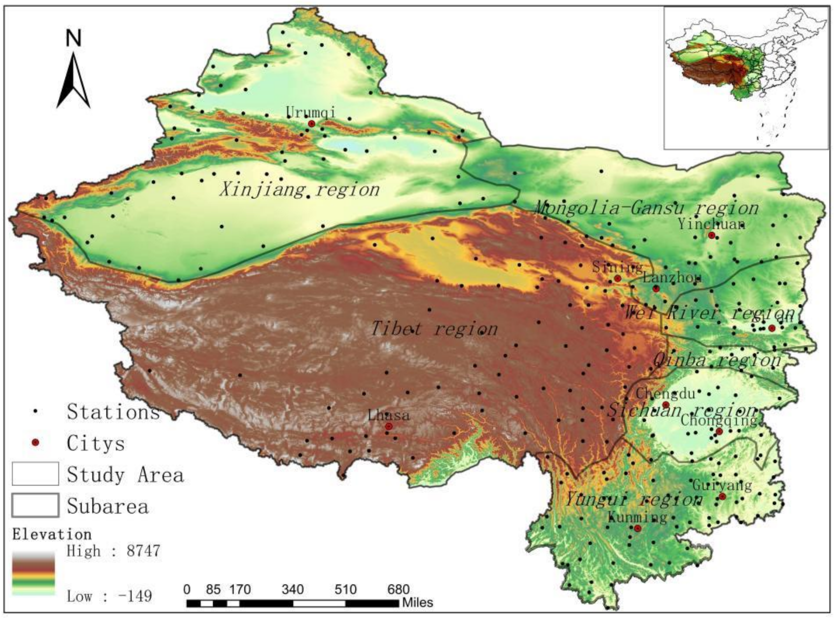

Figure 1. Study area with the position of weather stations.

2.2. Data

In this study, data from daily observation meteorological stations in western China were used. After the outlier processing and screening of undetected data stations, data from 332 meteorological stations in the study area were selected. Meteorological elements included precipitation, daily mean temperature, average minimum temperature, average maximum temperature, sunshine duration, average wind speed, and relative humidity. The meteorological data were obtained from the "Daily Values of China Surface Climatological Data V3.0" (http://data.cma.cn, accessed on 5 March 2022) dataset of the National Meteorological Center of the China Meteorological Administration. The time span was 1960–2017, and the spatial resolution was 0.5°. The data were preprocessed using the MATLAB and SPASS platforms. The monthly values of meteorological data were calculated to facilitate the follow-up study. Meteorological data for 2018–2019 were supplemented by data from stations in the study area on the Wheat Agrometeorological Big Data platform.

The remote sensing data used in this paper included the GIMMS NDVI 3 g V1.0 data product, which was downloaded from the Tibetan Plateau Scientific Data Center (http://data.tpdc.ac.cn, accessed on 29 May 2022). The time span was 1982–2015, and the spatial resolution was 8 km. MODIS MOD13Q1 data products were downloaded from the Google Earth Engine platform (https://developers.google.com, accessed on 29 May 2022), across 2000–2019, with a time resolution of 16 d and a spatial resolution of 250 m. The GIMMS NDVI data were processed using Python, and the format, projection, and resolution of the GIMMS NDVI data were transformed using MATLAB, consistent with the MODIS NDVI data, to facilitate the subsequent comparative study. In addition, spatial resolution was also applied 30 m from the surface coverage data (Globe Land 30), via the 2010 version (http://www.globallandcover.com, accessed on 22 June 2022), to comparatively study the NDVI and the distribution of meteorological elements in the cross-correlation effect relationship.

2.3. Maximum Value Composite Method

Based on the MODIS NDVI data, this paper converts the spatial resolution and projection of the GIMMS NDVI dataset, resampling the spatial resolution to 250 m to make it consistent with the MODIS NDVI. At the same time, the scope of the two datasets was trimmed based on vector data to reflect the research range of the study (the western region). After the two kinds of NDVI data underwent the pre-processing process of resampling, data clipping, projection conversion, etc., GIMMS NDVI data and MODIS NDVI data of monthly scale were obtained by the maximum value synthesis method to further eliminate the difference between the two datasets, to extend the NDVI data and use it for follow-up continuity research [25]. The vegetation growth season was determined to be from May to September in western China, and the time lag effect between vegetation growth season and the humidity index was analyzed.

2.4. Calculation of Evapotranspiration and Humidity Indexes

The humidity index can reflect the dynamic equilibrium state of precipitation and evapotranspiration over a certain period of time in the study area, and represent the degree or trend of dry and wet changes over a certain period of time in a certain area. In this paper, the ratio of precipitation to potential evapotranspiration, namely the humidity index (I), was used as the dry–wet index to characterize the dry–wet degree of the long time series of 1960–2019 in western China. The formula is as follows:

$$I = P/ET_0 \tag{1}$$

where I is the humidity index, P is precipitation (mm), and ET_0 is the maximum possible evapotranspiration (mm). The greater the humidity index in the study area, the wetter the climate in the area. Conversely, the smaller the humidity index, the drier the climate. Based on the International Convention to Combat Desertification [26], the climate was divided into five regions: extremely arid zone (humidity index $\leq$ 0.05), arid zone (0.05–0.20), semi-arid zone (0.20–0.50), semi-humid zone (0.50–0.65), and humid zone (>0.65).

Potential evapotranspiration (ET_0) was analyzed The Penman–Monteith model (P–M model), recommended and revised by FAO in 1998, was used for calculation. The equation and elements were as follows:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273.15}U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{2}$$

where ET_0 is the potential evapotranspiration, R_n is the net radiation, G is the soil heat flux, γ is the constant of the hygrometer, T is the average air temperature at 2 m above the surface, U_2 is the average wind speed at a height of 2 m above the surface, e_s, e_a are the saturated water vapor pressure and the actual water vapor pressure, and Δ is the slope of the saturated water vapor pressure curve at the current air temperature.

2.5. Correlation Analysis

Using MATLAB, the Pearson correlation analysis method was used in this paper to analyze the correlation between the NDVI and the humidity index in the growing season [27]. Moreover, the time-delay cross-correlation analysis method at the pixel scale is further adopted to analyze the correlation between the NDVI and the humidity index [28–34]. The calculation formula is as follows:

$$r = \frac{\sum_i^n\left[\left(X_{(i)} - \overline{X}\right) \times \left(Y(\mathrm{i}-l) - \overline{Y}\right)\right]}{\sqrt{\sum_i^n\left(X_{(i)} - \overline{X}\right)^2}\sqrt{\sum_i^n\left(Y(\mathrm{i}-L) - \overline{Y}\right)^2}} \tag{3}$$

where r is the cross-correlation number, i is the month, n is the total number of months, L is the lag time, in months, $X_{(i)}$ is the corresponding NDVI value of the month, $Y(\mathrm{i}-l)$ is the corresponding humidity index, and $(\mathrm{i}-l)\overline{X}, \overline{Y}$ is the mean value. Since the degree of dryness and wetness only affects the change in the NDVI in the growing season, this paper only considered the time-lag effect from May to September.

2.6. Inverse Distance Weight (IDW) Interpolation

The inverse distance weight interpolation method is a direct spatial surface interpolation method based on the assumption that the known sample points have a local influence on the prediction of the predicted point values, and the influence decreases with the increase in the distance [35]. The principle is simple, the operation is simple, and the result is better. In this study, surface interpolation of the humidity index was carried out in ArcGIS10.7, to conduct spatial differentiation analysis.

Based on the above data and methods, the flowchart of this study is shown in Figure 2.

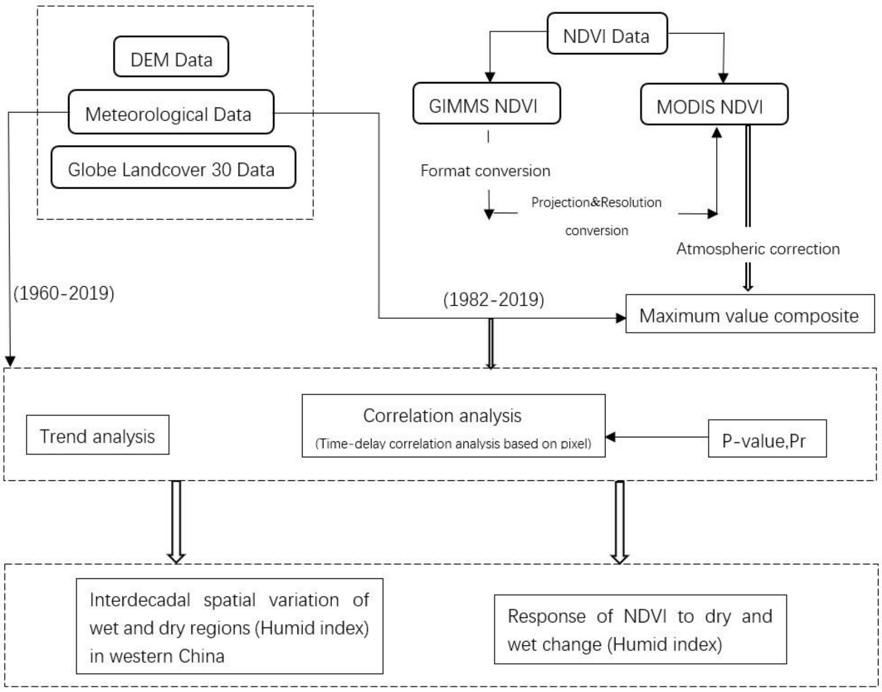

Figure 2. Flowchart of the study.

3. Results

3.1. Interdecadal Spatial Distribution and Variation in Humidity Index

Based on the calculated annual humidity index data of 332 meteorological stations in the western region, the spatial distribution map of the interdecadal humidity index in each region from the 1960s to the 2010s was drawn based on the IDW interpolation method in ArcGIS, and the spatial variation characteristics of dry and wet conditions in each region were analyzed.

1. Menggan Region. The humidity index of the Menggan region reaches a minimum in the Badain Jaran Desert and its surrounding areas, and a maximum in the south of the Yinshan Mountains to the north of Ordos and the Gannan region. Over the past 60 years, the extent of extremely arid areas in Menggan District has gradually decreased from 11.43% in the 1960s to 5.16% in the 2010s, while the extent of semi-arid areas has experienced a change process of first decreasing and then increasing, and the total area today is largely equal to that in the 1960s. As shown in Table 1.

Table 1. Area statistics of dry and wet zones in the study area.

Partition	Extremely Arid Zone	Arid Zone	Half Arid Zone	Semi-Humid Zone	Wet Zone
Menggan area	−6.27%	4.10%	1.48%	0.57%	0.12%
The Weihe area	\	−0.02%	5.69%	−9.18%	3.50%
The Qinghai-Tibetan area	−2.67%	−27.14%	0.89%	19.83%	9.08%
Xinjiang area	−12.13%	6.17%	−5.07%	6.50%	4.53%
Yunnan-Guizhou area	\	\	−0.88%	−2.92%	3.80%
Sichuan area	\	0.1%	−0.67%	−0.40%	1.17%
Qinba area	\	\	1.59%	0.20%	−1.79%

Positive values in the table represent the overall increase in a wet and dry area over the past 60 years, while negative values represent the decrease.

2. Weihe Region. The changes in semi-arid and sub-humid areas in the Weihe region showed opposite trends. The extent of semi-arid areas showed an overall increase, but decreased significantly in the 1980s and 2000s, from 11.40% to 38.19% and then to 17.09%, mainly in the Weihe River region in the Loess Plateau. In the 2000s, the extent of subhumid areas decreased from 73.60% in the 1960s to 24.57% in the 1990s and then to 64.42% in the 1990s. The change range is mainly distributed in the north of the Qinling Mountains and the south of Guanzhong Plain, such as Shangluo City and Baoji City.
3. Qinghai–Tibet Region. As shown in Figure 3, the extent of extremely arid and arid regions in the Qinghai–Tibet Plateau has decreased from 4.54% in the 1960s to 1.87% in the 2010s, mainly in the northern part of Qaidam District and the western part of the Qilian–Qinghai Lake region. The extent of arid areas decreased from 42.82% to 17.56%, mainly in western Shigatse and Ngari. The extent of subhumid and humid areas increased significantly, from 5.94% in the 1960s to 25.77% in the 2010s for subhumid areas, and from 2.15% to 11.23% for humid areas, mainly in the Bomi–West Sichuan area.

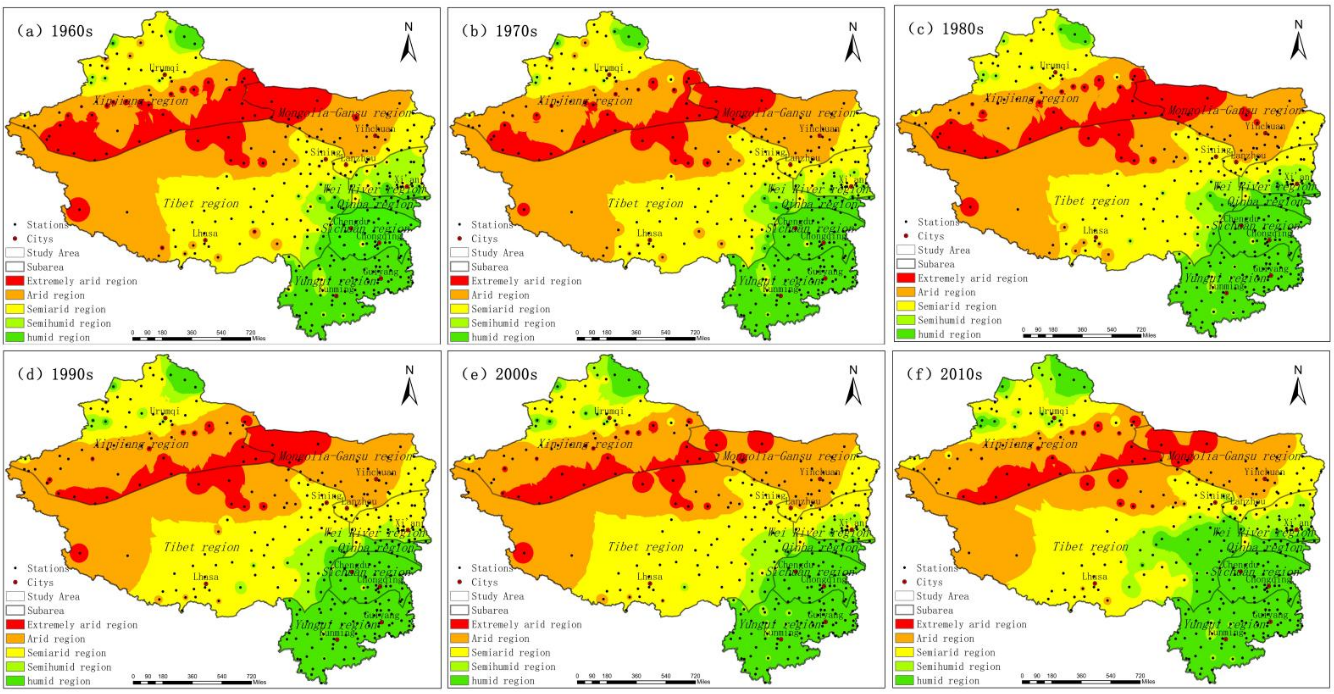

Figure 3. Decadal distribution and variation of dry and wet areas in western China.

4. The Xinjiang region. Over the past 60 years, the Xinjiang region has shown a trend of continuous wetting. The extent of extremely dry areas decreased from 23.40% to 11.27%, mainly in the southern part of southern Xinjiang, from Kashgar to Hotan. As shown in Table 1, The extent of semi-arid areas decreased from 27.84% to 22.77%; subhumid areas increased from 3.16% to 9.66%; and humid areas increased from 3.33% to 7.86%, mainly in the Yining area, the Tacheng area, and the fertile area in the north of Altay.
5. The Yunnan–Guizhou region. As a whole, the climate in the Yunnan–Guizhou region is relatively humid, as shown in Figure 3. Variations in the humidity index in this region mainly occur in the northern part of Chuxiong Prefecture and on the western side of the Wumeng Mountains. Over the past 60 years, the extent of semi-arid areas decreased from 1.14% to 0.26%, humid areas increased from 93.24% to 97.04%, while subhumid areas decreased slightly from 5.62% to 2.70%.
6. The Sichuan region. The semi-arid area of Sichuan, including Chongqing, was mainly distributed in Neijiang and Ziyang, and its extent decreased from 0.67% in the 1960s to 0.22% in the 2000s, and then there was no semi-arid area in the 2010s. The extent of humid areas increased from 98.47% to 99.64%.
7. Qinba Region: The Qinba District is located in southern Shaanxi and the upper reaches of the Han River. The north subtropical monsoon climate and warm-temperate monsoon climate are both humid. The area of each humid or subhumid area hardly changed during the period covered by the study and is largely stable. However, there is an increasing trend in the extent of semi-arid areas.

The spatial distribution of the interdecadal mean humidity index in the western region is significantly different. Based on the distribution of, and variations in, the average humidity index in each region, a gradually increasing trend to the northwest and southeast, from the northwestern region of the Qinghai–Tibet Plateau to the northern region of the Qilian Mountains, can be detected. The low-value centers are in the southern part of the Taklimakan Desert, along the northern side of the Altun Mountains and the Badain Jaran Desert. High values of the humidity index are mainly concentrated along the western side of the Sichuan Basin, the Hengduan Mountains, the northern part of the Sichuan Basin, and the northern part of the Junggar Basin. The distribution of high and low values of the humidity index is very obvious and consistent with that of desert bare land, desert coverage, and precipitation in western China. It can be considered that the humidity index has significant interaction with the vegetation type or precipitation distribution in western China.

3.2. Time-Delay Mutual Correlation between the NDVI and the Humidity Index

In order to study the spatial correlation between the NDVI and the humidity index, this paper discusses the time-delay mutual correlation between changes in the NDVI and the humidity index at the pixel scale. Based on cross-correlation theory, the correlation number of the pixel-scale NDVI and the humidity index under each time delay in the growing season was calculated. Then, the maximum correlation number in the pixel-scale NDVI and the humidity index and its corresponding lag time were calculated using MATLAB, and the correlation number results were tested for significance. The p-value was used for division purposes. If the p-value was less than 0.05, it was considered significant. In this way, the spatial correlation between the NDVI and the humidity index was revealed.

There was a significant positive correlation between the NDVI and the humidity index in the western region ($p < 0.05$).

(1) The spatial distribution of maximum cross-correlation between the NDVI and the humidity index in the Menggan region shows that the maximum cross-correlation between the NDVI and the humidity index presents a significant positive correlation in spatial distribution, as shown in Figure 4a. About 97.65% of the regions had a positive correlation between the NDVI and the humidity index, and the correlation number was greater than 0.2. The regions with a strong positive correlation were mainly distributed in Lanzhou,

Baiyin, and southwestern Ordos, and the ecosystem type was mainly grassland. About 0.003% of the region's NDVI and the humidity index showed a weak negative correlation, and the correlation number was greater than 0.04.

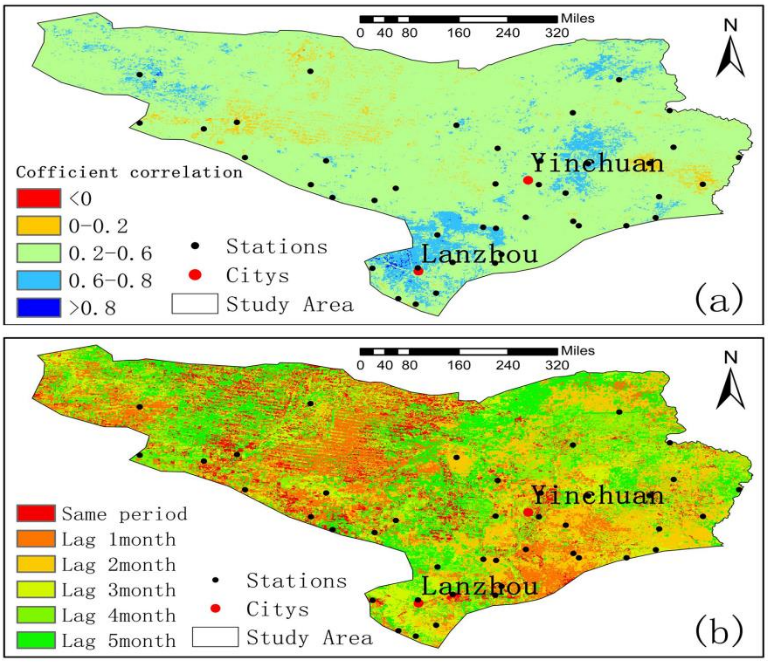

Figure 4. Spatial distribution of maximum cross-correlation (**a**) between NDVI and humidity index and time-lag response (**b**) in the Menggan region.

As shown in Figure 4b, the spatial distribution of the time lag of changes in the NDVI to changes in the humidity index showed that changes in most of the NDVIs in the Menggan District lagged those in the humidity index by 2 months or 5 months, accounting for 22.72% and 22.42%, respectively, followed by a one-month lag, accounting for 19.75%, and 7.71% of areas had an NDVI and humidity index changing in the same period. Changes in the NDVI lagged those in the humidity index by 2 months, mainly in the southern part of Ordos City, the southeast part of Ningxia, and the eastern part of the Gansu Province. The ecosystem types mainly involved grassland, shrub, and bare land. The regions with an NDVI and a humidity index lagging by 5 months were mainly to be found in the west of the Alxa League, mainly covering forests and bare land. The areas with the same period of NDVIs and humidity indexes were mainly to be found in the western part of the Alxa League and the western part of the Ulan Buhe Desert, and the main ecosystem type was bare land.

(2) There was a positive correlation between the NDVI and the humidity index in the Weihe River region, and 94.03% of the regions had a correlation number greater than 0.2, and there was no negative correlation within the region.

In most of the Weihe District, the NDVI lagged the humidity index by 1 month or 3 months, accounting for 47.39% and 26.52%, respectively. Only 3.48% of the regions had the same NDVI and humidity index. As shown in Figure 5b, the regions with the same period of the NDVI and the humidity index were mainly to be found in the central part of northern Shaanxi, and the main ecosystem types were grassland and cultivated land. The areas with an NDVI lagging the humidity index by 1 month were mainly to be found on both sides of the Guanzhong Plain, and the ecosystem types were grassland, cultivated land, and forests. The areas with an NDVI lag of 5 months were mainly to be found in the eastern part of Tianshui and the southern part of Dingxi, and the main ecosystem type was forests.

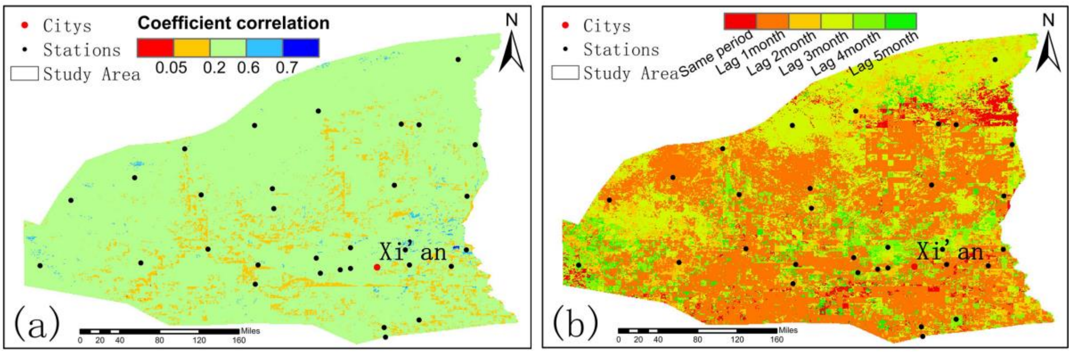

Figure 5. Spatial distribution of maximum cross-correlation (**a**) between NDVI and humidity index and time-lag response (**b**) in the Weihe region.

(3) The positive correlation between NDVI and humidity index was about 92.56% in the Qinghai–Tibet region, and the strong positive correlation was mainly to be found in the southern slope of the northern Tibetan Plateau and the Golmud area in the south of the Qaidam Basin. As shown in Figure 6a. The ecosystem types were mainly grassland and a few areas of shrubland.

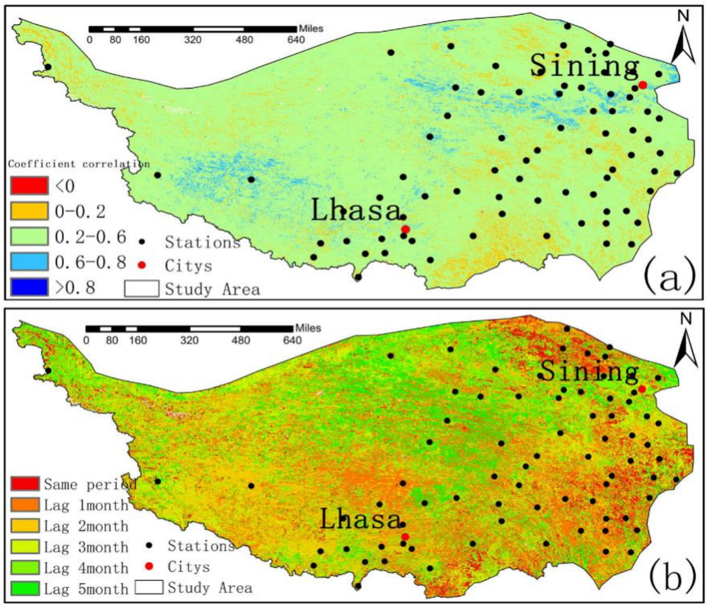

Figure 6. Spatial distribution of maximum cross-correlation (**a**) between NDVI and humidity index and time-lag response (**b**) in the Qinghai-Tibet region.

In total, 23.01% of the Qinghai–Tibet region's NDVI lagged the humidity index by 2 months, followed by a 1-month lag, which accounted for 22.92%. The NDVIs were widely distributed in central and southern Tibet, and the ecosystem type was grassland and parts of bare land. The regions with the same period of NDVIs and humidity indexes could be found in the Qilian–Qinghai Lake region and the western Sichuan–Bomi region, and the ecosystem types were grassland, bare land, and a small area of planted forest, accounting for 7.88%. As shown in Figure 6b. This is generally consistent with the reduction in the extent of extremely arid and arid areas in the division of dry and humidity indexes and is generally consistent with the positive and weak correlations between the NDVI and the humidity index. This indicates that the positive correlation between the NDVI and the humidity index is more sensitive in this region; thus, the positive impact is more sensitive and the response of grassland in the ecosystem is the most sensitive.

(4) In Xinjiang, the regions with a strong positive correlation between the NDVI and the humidity index were mainly to be found in the Alashan Estuary, Urumqi, and the

Yili Valley on the north side of Aibi Lake. The ecosystem types were mainly grassland, sparse grassland, and small forest distribution areas on bare land margins. The positive correlation accounted for 92.77% of the regions, as shown in Figure 7a. The regions with weak positive correlation were mainly to be found in the Tarim Basin and the Taklimakan Desert, and the ecosystem type was mainly bare land.

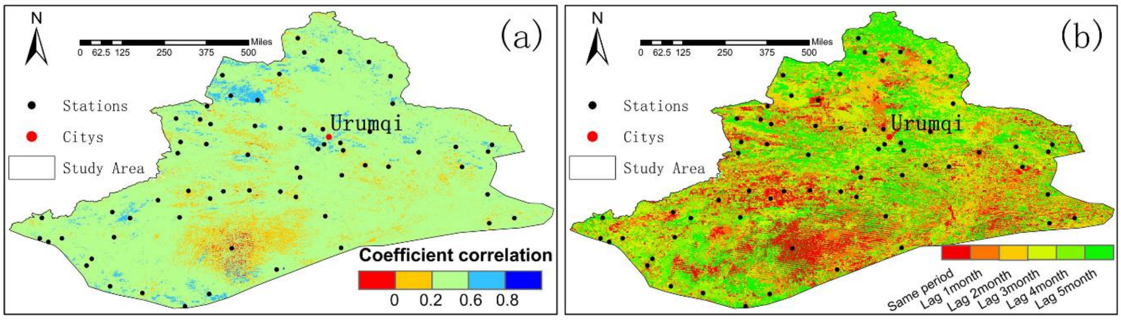

Figure 7. Spatial distribution of maximum cross-correlation (**a**) between NDVI and humidity index and time-lag response (**b**) in the Xinjiang region.

Moreover, the regions where the NDVI and the humidity index in Xinjiang varied during the same period accounted for 14.50% of the total, as shown in Figure 7b, and were mainly to be found in the Taklimakan Desert and the southeastern Aksu region, and the ecosystem type was bare land. In addition, the regions where changes in the NDVI lagged the humidity index by 5 months or 3 months accounted for 23.71% and 20.29% of the total, respectively, and were widely distributed in southern and northern Xinjiang.

(5) In the Yunnan–Guizhou region, there was no negative correlation between the NDVI and the humidity index, and the correlation coefficient was greater than 0.2 in the area, which reached 94.07%.

In the Yunnan–Guizhou region, the regions where the NDVI and the humidity index varied in the same period accounted for 20.84% of the total, as shown in Figure 8b. These regions were mainly to be found in the eastern Yunnan Plateau and southwestern Guizhou, and the ecosystem types were relatively complex, with extensive grassland and a mixed distribution of cultivated land and woodland. The regions where changes in NDVIs lagged the humidity index by one month accounted for 25.85% of the total and were mainly to be found in the northwest of the Yunnan–Guizhou Plateau and the east of Erhai Lake, and the ecosystem was mainly grassland and alpine forest. The area where the NDVI lagged the humidity index by 5 months was mainly to be found in the Wumeng Mountains and the Dalou Mountains, and the main ecosystem type was woodland, accounting for 10.64%.

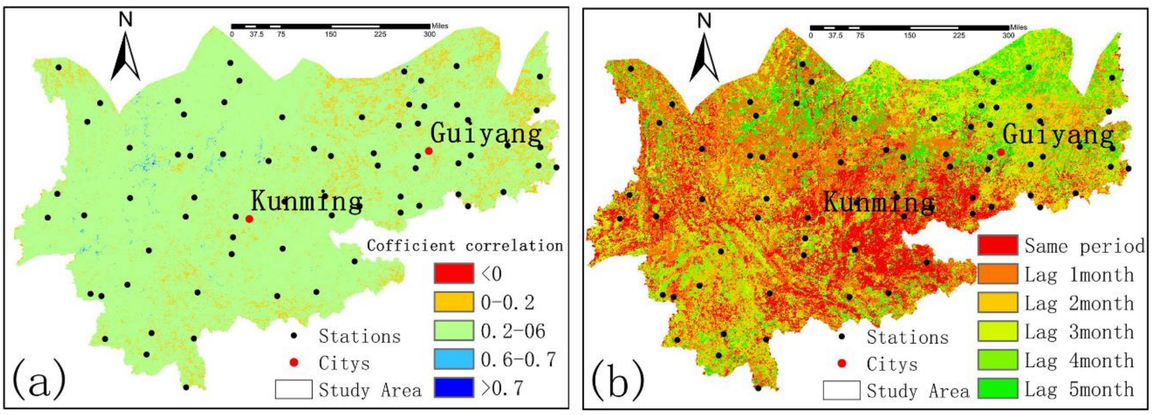

Figure 8. Spatial distribution of maximum cross-correlation (**a**) between NDVI and humidity index and time-lag response (**b**) in the Yunnan-Guizhou region.

(6) The maximum correlation degree between the NDVI and the humidity index in the Sichuan region had a low value, and the correlation number was −0.26. The area with a negative correlation accounted for 0.03% of the region, and the area with a maximum positive correlation was about 88.67%. The ecosystem types were mainly grassland and forest.

As shown in Figure 9b, in 28.62% of regions, changes in the NDVI lagged those in the humidity index by 3 months in Sichuan, and these were mainly to be found in Leshan and Ya'an in the northern margins of the Daliang Mountains, and the ecosystem type was woodland. The proportion of regions where the NDVIs and humidity indexes varied in the same period was 17.42%, and these were mainly to be found in the eastern part of the Mianyang and Guangyuan areas, and the main ecosystem types were grassland and cultivated land. The regions with changes in the NDVI lagging behind those in the humidity index by 5 months were mainly located in the middle and low mountainous areas of southeast Chongqing, accounting for about 9.03%, and the ecosystem type was mainly woodland.

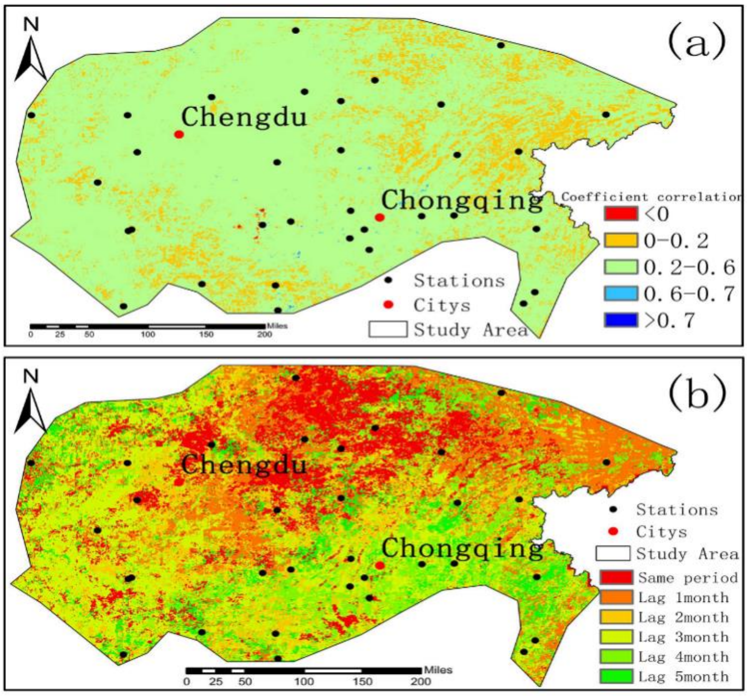

Figure 9. Spatial distribution of maximum cross-correlation (**a**) between NDVI and humidity index and time-lag response (**b**) in the Sichuan region.

(7) The maximum positive correlation between the NDVI and the humidity index was 95.78% in the Qinba area, which was widely distributed in the Hanzhong Basin, while a weak positive correlation was mainly distributed in the western Qinling Mountains.

The regions with the same period of NDVIs and humidity indexes were mainly to be found in the central and northern parts of Ankang and the southern part of Hanzhong, and the ecosystem types were grassland and cultivated land. As shown in Figure 10b. The NDVI lagged the humidity index by 5 months in the eastern margin of the Micang Mountains and southeast of the Hanzhong Basin, accounting for 11.18%, and the ecosystem type was mainly woodland.

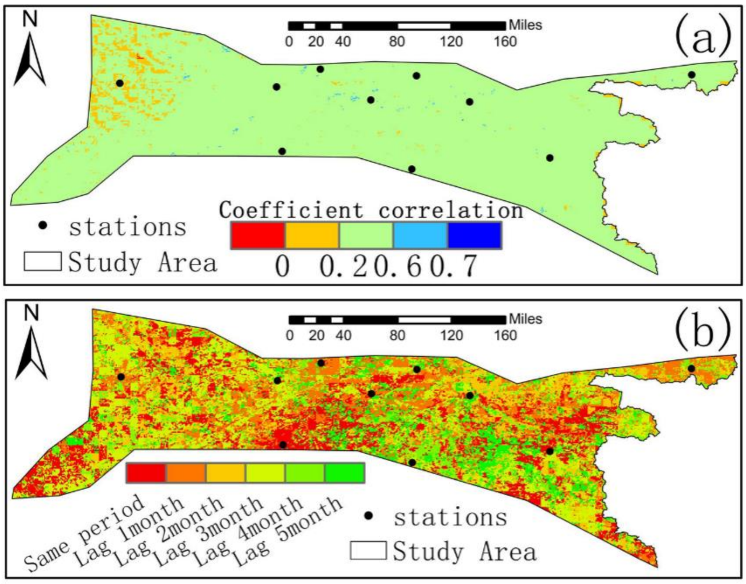

Figure 10. Spatial distribution of maximum cross-correlation (**a**) between NDVI and humidity index and time-lag response (**b**) in the Qinba region.

The spatial distribution of the maximum cross-correlation between the NDVI and the humidity index shows that the maximum cross-correlation number of NDVIs and humidity indexes is significantly different in the whole western region. About 99% of the regions in the study area had a positive correlation between the NDVI and the humidity index, and the correlation number was greater than 0.2. Between them, the time-delay correlation number was in the region of 0.6–0.8, accounting for about 85%, which was widely distributed in the whole study area in western China. The time-delay mutual relation number was about 7% in the region of 0.2–0.6 and mainly distributed in the Aksu region, the Hotan and Bayingoleng Mongolian Autonomous Prefecture of Xinjiang, the border area of the prefecture, southwest Zetang County, and the Nyingchi County of Tibet. The vegetation types were mainly grassland and desert grassland, including a small proportion of woodland. When the correlation number was greater than 0.8, the regions with a significant positive correlation accounted for about 8%, mainly distributed in the west of Tacheng of Xinjiang, Lanzhou, and Pingliang of Gansu, the surrounding areas of Ulan, the west of Nagqu of Tibet, and the southeast of Ggar, and the vegetation type was mainly grassland.

4. Discussion

On the whole, the degree of wetness in western China, especially in northwest China, has increased, and the degree and trend of wetness have increased, such as in the northwest of Xinjiang, the west of Menggan, the northwest of Qinghai–Tibet, etc., findings which are generally consistent with the conclusions of previous studies. Nevertheless, some studies have come to a different conclusion. For example, in this study, it was found that the scope and area of extremely arid and arid areas within the region decreased in the Qinghai–Tibet region, while Zhao et al. [19] found that the degree of dryness in some areas in the middle of the Qinghai–Tibet region gradually increased. This may be because this paper only calculates the humidity index on the level of precipitation and evapotranspiration to divide the dry and wet areas and further explore the changes in regional dry and wet trends, while Zhao et al., expounded their research and predicted the dry and wet conditions in China from the perspective of agriculture, with different classification focuses and research periods. It is worth mentioning that although some regions experienced a tortuous process of first drying and then wetting, from the perspective of a long time series, trends in the degree of wetting were significant in western China, especially in the semi-arid and semi-humid ecosystem-sensitive areas.

In terms of the correlation between the NDVI and the humidity index in western China, the correlation number between the NDVI and the humidity index was positively correlated with the spatial distribution of the time-lag effect, and the time-lag in each region was different due to different geographical locations and climatic conditions. For example, in this study, the NDVI in the Qinghai–Tibet region had the strongest response to dry and wet changes (at the same time) in the northeastern and eastern parts of the Qinghai–Tibet region, which is consistent with the research results of Liu et al. [36]. In their research assessing the quantitative impact of climate change on the alpine grassland vegetation dynamics of the Qinghai–Tibet Plateau, they pointed out that the NDVI in the growing season gradually decreased from northeast to southwest. The annual growth rate of evaporation in the growing season significantly decreased. The evaporation in the growing season was the main direct influencing factor, while the average relative humidity and precipitation in the growing season were indirect influencing factors. The average temperature of the growing season had a minor effect on vegetation dynamics. The difference is that this study did not make an in-depth study of the causes and contributions affecting the dynamic changes in dry and wet vegetation. If possible, this will be further explored in subsequent studies. In terms of vegetation types, grassland, desert grassland, and cultivated land had the most sensitive responses to dry and wet changes, and had the shortest time-delay responses in most areas, followed by bare land, shrub, or cultivated land. Finally, woodland had the least sensitive responses to dry and wet changes, as this ecosystem is more complex and stable. This is consistent with the research results of Na et al. [37] on the diversity response of vegetation dynamics regarding climate change in Inner Mongolia. In addition, Na et al., divided factors in climate change events in detail to explore the impact on vegetation, indicating that typical grassland, desert grassland, and forest grassland areas were more sensitive to extreme precipitation, while forest areas were more sensitive to extremely warm temperatures. The effect of extreme precipitation on vegetation was delayed by one month, which was greater than that on the grassland system in the same month. The effect of extreme temperature on vegetation in the same month was greater than that on the forest system.

Due to the large overall scope of the study area, it cannot be ruled out that the time delay of effects on vegetation was affected by factors such as high altitude, alpine zone, and human causes. In addition, due to the limitations of topographic and natural environment factors, the spatial distribution of meteorological stations in the study area was not uniform, which will cause inevitable errors in the spatial interpolation of data. In view of the large-scale and long time series studies in western China, there were not enough studies on the synergy of factors affecting vegetation dynamics at the regional level. In the overall level of western China, this study will eliminate the interference of cultivated land and planted forests as much as possible in the subsequent work, and quantify the relative contribution of specific meteorological factors, such as temperature, precipitation, relative humidity, and sunshine duration.

5. Conclusions

In this paper, based on the meteorological element data of the western regions of China over the past 60 years, the humidity index of western China under a wide range of long time series was calculated for the different regions. Combined with MODIS and GIMMS-NDVI data, the cross-correlation effect between them was explored, and the cross-correlation response of dry and wet changes and vegetation in the western region was analyzed from the spatial scale. The following conclusions can be drawn:

(1) Over the past 60 years, the west of China has tended to be humid, on the whole, and the areas of extremely arid and arid areas have decreased. Climate-sensitive areas, such as semi-arid and sub-humid regions, have great fluctuations, which is the case with the Weihe and Menggan regions. There was a significant positive correlation between the NDVI and the humidity index in most regions ($p < 0.05$). For example, the NDVI was positively correlated with a humidity index of 97.65% in the Menggan region ($p < 0.05$),

consistent with the area of high wetness in the south of Ordos and eastern Gansu. In the Xinjiang and Qinghai–Tibet subregions, the positive correlations between the NDVI and the humidity index ($p < 0.05$) were 92.77% and 92.56%, respectively.

(2) Due to the large study area and significant differences in vegetation types and topographies, the lag times in changes in the NDVI in each area were not consistent. For example, in most areas in the Menggan area, changes in the NDVI lagged those in the humidity index by 2 months or 5 months, and the ecosystem types were mainly shrub, bare land, and woodland. In total, 47.39% of the Weihe region's NDVI lagged the humidity index by one month, mainly to be found on both sides of the Guanzhong Plain, and the ecosystem types were grassland, cultivated land, and areas of woodland. Moreover, 28.62% of Sichuan's NDVI lagged the humidity index by 3 months and was mainly to be found in Leshan and Ya 'an in the northern margin of the Daliang Mountains. In the Yunnan–Guizhou area, areas with a delayed response time were mainly to be found in the northwest of the Yunnan–Guizhou Plateau and the east of Erhai Lake. The ecosystem was dominated by grassland and alpine forest. Although the response time of the NDVI to the humidity index was inconsistent in different regions, it can still be observed that among different vegetation types, grassland, cultivated land, and shrub were more sensitive to the humidity index, while woodland, forest, and other ecosystems were more stable and slow to respond. For example, in Xinjiang, the NDVIs and humidity indexes mainly varied in the same period in the Qilian–Qinghai Lake area and the western Sichuan–Bomi area, which was generally consistent with the decreasing range of extremely arid and arid areas and was generally consistent with the area with a positive correlation between the NDVI and the humidity index ($p > 0.05$), indicating that a positive correlation between the NDVI and the humidity index in this region means that the positive effect is more sensitive and the response of grassland is the most sensitive in the ecosystem.

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