Effects of Climatic Factors and Human Activities on Vegetation Change in Gansu Province from 2001 to 2023

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Abstract

Gansu Province is a key ecological barrier area in western China, characterized by poor site conditions, ecological fragility, and intensive human activities. Vegetation is an "indicator" of regional ecological conditions, and studying how its changes are affected by climatic factors and human activities is of great significance for revealing ecological evolution in Gansu Province. Using enhanced vegetation index, annual mean precipitation, and annual mean temperature data, this study applied statistical methods to analyze vegetation changes in Gansu Province over 24 a and the influences of climatic factors and human activities. The results show that: (1) the vegetation growth rate in Gansu Province was 0.0033 · a-1, with significant increases in forests and grasslands. (2) Vegetation changes were stable in the Longdong Loess Plateau, Gannan Plateau, and Qinba Mountains, accounting for 65.2%; the Longzhong Loess Hilly Region, Hexi Corridor, and Beishan area showed fluctuations, accounting for 35.7%. Overall, vegetation changes exhibited sustained growth, while localized areas in Gannan, Longzhong, and Hexi showed a sustained decreasing trend. (3) Climatic factors were the dominant drivers of vegetation growth, among which precipitation showed a positive correlation over 80.11% of the area, while temperature exhibited a relatively weak negative effect. The influence of human activities on vegetation change indicates that the Hexi Corridor and Beishan area, the Longzhong Loess Hilly Region, and the Longdong Loess Plateau were positively affected by human activities, whereas parts of the Gannan Plateau and Qinba Mountains were inhibited.

Full Text

Effects of Climatic Factors and Human Activities on Vegetation Change in Gansu Province from 2001 to 2023

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Abstract: Gansu Province is a key ecological security barrier area in western China. It has poor site conditions, a fragile ecology, and intense human activities. Vegetation is an "indicator" of regional ecological conditions; studying how its changes are affected by climatic factors and human activities is of great significance for revealing ecological degradation in Gansu Province. Using enhanced vegetation index, annual mean precipitation, and annual mean temperature data, this study applied statistical methods to analyze vegetation change in Gansu Province over 24 years and the effects of climatic factors and human activities on it. The results show that: (1) The growth rate of vegetation in Gansu Province was $0.0033 \cdot a^{-1}$, with significant increases in forests and grasslands. (2) Vegetation change was stable in the Longdong Loess Plateau, Gannan Plateau, and Qinba Mountains, accounting for 65.2%; it fluctuated in the Longzhong Loess Hills, the Hexi Corridor and Beishan region, accounting for 35.7%. Overall, vegetation change showed sustained growth, while local areas in Gannan, Longzhong, and Hexi showed a trend of continuous decline. (3) Climatic-factor forcing was the dominant factor in vegetation growth; among these, precipitation showed a positive correlation over 80.11% of the area, while temperature showed a relatively weak negative effect. The influence of human activities on vegetation change showed positive effects in the Hexi Corridor and Beishan region, the Longzhong Loess Hills, and the Longdong Loess Plateau, while local areas of the Gannan Plateau and Qinba Mountains were inhibited by human activities.

Keywords: vegetation change; climatic factors; human activities; Gansu Province

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Vegetation ecosystems are all substantially affected by climate, the land-surface environment, and human activities[1-2]. Through multi-scale biogeochemical processes, vegetation participates in the regulation of the global climate system, and its photosynthesis-respiration processes constitute core links in the global carbon cycle[3-4]. The transpiration of vegetation drives regional water-heat balance, and vegetation also has important positive feedback mechanisms in terms of surface albedo. In regulating land-surface processes, vegetation has certain positive effects on water and soil conservation, landform shaping, soil improvement, and other aspects. In agricultural production, urbanization processes, and other areas, vegetation also plays an important role in regulating the local microenvironment[5-6]. As an important national ecological security barrier in western China, Gansu Province lies at the junction of the three major plateaus—the Loess Plateau, the Qinghai-Tibet Plateau, and the Inner Mongolia Plateau—and is located in an important region within the national ecological security strategic pattern of "Three Zones and Four Belts." However, because the underlying natural conditions are relatively poor, the ecology is fragile, and human activities are intense in most areas, it faces severe challenges to long-term sustainable socioeconomic development. Vegetation is an "indicator" of regional ecological conditions. Carrying out targeted research on the evolution of vegetation ecosystems, exploring the impacts of climatic factors and human activities on vegetation change in Gansu Province, is of great significance for formulating regional development strategies.

The proposal of remote-sensing vegetation indices has provided important data for monitoring vegetation change. Since the normalized difference vegetation index (NDVI) was proposed in 1974, it has been widely applied in many types of research, including ecological-environment monitoring, vegetation phenology analysis, carbon–nitrogen cycling, and auxiliary land-use classification[7-8]. Research on vegetation change and its influencing factors is relatively extensive, including studies of trends in vegetation change, spatial patterns, and factors affecting vegetation change[9-12]. Studies related to vegetation change in Gansu Province also already have a certain foundation. Research on vegetation-change trends has mainly evaluated the rate of regional vegetation change through linear regression analysis or the Theil–Sen trend method[13-15]. With the aid of Pearson correlation coefficients and Spearman correlation coefficients, studies have investigated climatic fac-

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relationship between factors and vegetation change, and on this basis define the influence of climatic factors on vegetation change [16–20]. With the deepening of research on vegetation-driving factors, the academic community has separated the driving factors of vegetation change into two categories—climatic factors and human activities—and there are also various separation methods. Linear regression and the coefficient of variation method are two commonly used approaches [21–22]. However, most of the above studies have explored the impact of climatic factors on vegetation based on simple correlation analysis, often neglecting the strong coupling that exists among meteorological variables such as temperature and precipitation. Especially in a transitional region such as Gansu Province, where climatic gradients differ markedly, how to eliminate interference from covariates and accurately quantify the independent contribution of specific climatic factors still requires further in-depth investigation.

In view of the above shortcomings, this paper takes 2001–2023 as the study period and Gansu Province as the study area. First, a linear regression model is used to quantify the rate of vegetation change; then partial correlation analysis is introduced, aiming to overcome the drawbacks of traditional simple correlation analysis in being unable to eliminate the influence of collinearity among meteorological variables. This method can, under the premise of controlling for the influence of temperature (or precipitation), effectively eliminate coupling interference among climatic factors, thereby accurately resolving the independent driving mechanism of precipitation (or temperature) on vegetation growth. On this basis, a binary linear regression residual model is constructed to quantitatively separate the impacts of climate change and human activities on vegetation change, and the spatial visualization form is used to systematically reveal the action patterns of the respective driving factors.

1 Data and Methods

1.1 Overview of the Study Area

Gansu Province is located in the northwestern inland region of China (32°11′–42°57′N, 92°13′–108°46′E). It is about 1,655 km long from east to west, and only 24 km wide at its narrowest point from north to south, with a total area of approximately 4.258×10^5 km^2, accounting for about 4.7% of the country' s total land area. It lies at the junction of the Loess Plateau, the Qinghai–Tibet Plateau, and the Inner Mongolia Plateau, and is a key corridor connecting the Central Plains with Northwest China and Central Asia. Gansu Province spans the subtropical humid zone, the temperate continental arid zone, and the alpine plateau cold zone. The annual mean temperature is 0–15 °C, and annual precipitation ranges from 36.6 to 760 mm. According to geomorphological conditions, it is divided into the Qilian Mountains, the southern Gansu Plateau, the Longdong Loess Plateau, the Longzhong Loess Hilly Region, the Hexi Corridor and Beishan Mountains, and the Qinba Mountains (Fig. 1). The river systems within Gansu Province belong to the Yangtze River, Yellow River, and inland river systems. The Yellow River basin accounts for 32.1% of the province' s total area, the Yangtze River basin accounts for 8.7%, and the inland river basin accounts for 59.2%.

Gansu Province administers 14 prefecture-level cities, has 2 minority autonomous prefectures and 7 minority autonomous counties, and has a permanent population of 2.46×10^7 people. It includes more than ten ethnic minorities, such as the Hui, Tibetan, Dongxiang, Yugur, and Bonan peoples. As of 2024, Gansu Province' s gross regional product was 1.30×10^{12} yuan, with agriculture, industry, and services accounting for 12.5%, 34.1%, and 53.4%, respectively. Calculated by permanent population, the per capita gross regional product of Gansu Province was 5.28×10^4 yuan.

1.2 Data Sources

The data used in this paper include: MOD09A1 surface reflectance data from 2001–2023, used to calculate the enhanced vegetation index (EVI), followed by annual maximum-value compositing; monthly precipitation and mean temperature data for 2001–2023; annual Chinese land-cover type datasets for 2001–2023; the 1:1,000,000 standard boundary of Gansu Province and the geomorphological zoning of Gansu Province. The projection coordinate system of all data is the Albers equal-area conic projection, and the geographic coordinate system is the CGCS2000 National Geodetic Coordinate System.

(a) Topography of Gansu Province

Legend

- Prefecture-level city
- Provincial boundary
- Municipal boundary
- Elevation/m: 5821, 578

Scale: 0 200 km

(b) Geomorphological zoning of Gansu Province

Legend

- Provincial boundary
- Hexi Corridor and Beishan Mountains
- Southern Gansu Plateau
- Qilian Mountains
- Qinba Mountains
- Longdong Loess Plateau
- Longzhong Loess Hilly Region

Scale: 0 200 km

Note: Based on the standard map approved with review number GS(2024)0650 from the Standard Map Service website of the Ministry of Natural Resources; the base-map boundaries were not modified. The same below.

Fig. 1 Schematic diagram of the study area

1.3 Research Methods

1.3.1 Vegetation Index Calculation and Preprocessing

EVI is an improvement of NDVI[^23]. EVI provides research data in many fields, such as agricultural management, ecological environment, climate change, and land-cover types. Given the special surface characteristics of Gansu Province, EVI was selected to reflect vegetation coverage, avoiding the influence of soil background in low-vegetation-coverage areas on the vegetation index and the shortcoming that high-vegetation-coverage areas tend to be overestimated. In this study, the remote-sensing cloud-computing platform was used to calculate EVI data at 8-day intervals from 2000 to 2023. The calculation formula is as follows:

$$\mathrm{EVI} = G \times \frac{\mathrm{NIR} - \mathrm{Red}}{\mathrm{NIR} + C_1 \times \mathrm{Red} - C_2 \times \mathrm{Blue} + L} \qquad (1)$$

where: EVI is the enhanced vegetation index; NIR is the reflectance in the near-infrared band; Red is the reflectance in the red band; Blue is the reflectance in the blue band. The coefficients introduced under different environmental conditions are, respectively: $G = 2.5$, $C_1 = 6$, $C_2 = 7.5$, and $L = 1$.

Because MOD09A1 reflectance data are affected by terrain, cloud cover, and other factors, data gaps occur. In this study, image missing values were processed by linear interpolation and the Savitzky-Golay (S-G) filtering method[^24] to improve the quality of the EVI data. The calculation formulas are as follows:

$$y_i = y_1 + \frac{t - t_1}{t_2 - t_1} \times (y_2 - y_1) \qquad (2)$$

$$\hat{y} = \sum_{j=-k}^{k} c_j y_{i+j} \qquad (3)$$

where: y_i is the linear interpolation result of the image in period i; y_1 and y_2 are the pixel values at the two time points before and after the image in period i; t is the time point of the current period i; t_1 and t_2 are the times before and after the time point of period i; $\hat{y}$ is the smoothed data value; k is the half-window width, which determines the range of data participating in smoothing; j is the position index within the window; c_j is the convolution coefficient of the S-G filter, determined by the window size and polynomial order; and y_{i+j} is the original data point in the neighborhood.

1.3.2 Statistical Analysis Methods

(1) The linear regression method can analyze, pixel by pixel, the trend and magnitude of vegetation change within the time-series range. When the regression coefficient is greater than 0, vegetation increases; otherwise, it decreases[^25]. (2) The partial correlation coefficient is used to assess the degree of influence of different climatic factors on vegetation coverage. Its advantage is that, while measuring the correlation between two sets of variables, it excludes the interference of a third control variable[^26-27]. (3) The coefficient of variation is a statistic that measures the degree of variation in time-series vegetation, denoted as C_{EVI}; the larger its value, the greater the fluctuation of the EVI value in the time series, and conversely, the more stable it is[^28]. (4) The Hurst exponent (H) can describe the sustainability of a time-series vegetation index[^29]. When $0.5 < H < 1$, it indicates that the vegetation-coverage condition is consistent with the past; when $0 < H < 0.5$, it indicates that the vegetation-coverage condition is opposite to the past, and the closer its value is to 0, the stronger the anti-persistence.

1.3.3 Residual Analysis

Residual analysis is used to study the effects of human activities and climatic factors on vegetation change[^30]. Taking the vegetation index as the dependent variable and precipitation and temperature data as independent variables, the estimated values were fitted. The difference between the observed EVI values and the estimated EVI values was used as the impact of human activities on vegetation. The calculation formulas are as follows:

$$\mathrm{EVI}_{\mathrm{est}} = a \times P + b \times T + c \qquad (4)$$

$$\mathrm{EVI}_{\mathrm{res}} = \mathrm{EVI}_{\mathrm{obs}} - \mathrm{EVI}_{\mathrm{est}} \qquad (5)$$

where: $\mathrm{EVI}_{\mathrm{est}}$ is the estimated EVI value; a, b, and c are model parameters; P and T are the mean annual precipitation and mean annual temperature, respectively; and $\mathrm{EVI}_{\mathrm{res}}$ is the residual between the observed value $\mathrm{EVI}_{\mathrm{obs}}$ and $\mathrm{EVI}_{\mathrm{est}}$.

2 Results and Analysis

2.1 Spatiotemporal Variation Analysis of Vegetation Coverage in Gansu Province

Compared with the original images, the images after linear interpolation and S-G filtering show relatively good continuity and smoothness throughout the time series (Fig. 2). Figure 2b–c compares the EVI data before and after processing; the spatial continuity and smoothness are both better than those of the original data.

2.1.1 Analysis of Temporal Changes in Vegetation Coverage Over the past 23 years, the overall vegetation coverage in Gansu Province has shown an upward trend, with a vegetation growth rate of approximately $0.0033 \cdot \mathrm{a}^{-1}$ (Fig. 3a). From 2001 to 2012, vegetation change exhibited relatively strong fluctuations. After 2012, vegetation growth reached the peak of the study time series; the provincial mean EVI rose from 0.33 to 0.37, then showed a declining trend, until a relatively obvious growth trend appeared after 2016, followed again by a declining trend from 2020 to 2023 (Fig. 3a). The spatial pattern of vegetation change was as follows: vegetation growth was relatively evident in the Longdong Loess Plateau, the Longzhong Loess Hilly Region, most of the Qinba Mountains, and the Gannan Plateau. In the central part of the Gannan Plateau, vegetation showed moderate and slight decreasing trends. Vegetation in the Hexi Corridor and the Beishan Mountains mostly increased significantly, while vegetation decreased relatively rapidly in western Dunhuang City, located in the western part of the Hexi Corridor and the Beishan Mountains. From pixel-based statistics of vegetation increase and decrease, 39.67% of the area showed slight growth, Figure panel: (a) Time-series curves before and after S-G filtering. Legend: EVI; S-G EVI. Vertical axes: EVI; S-G EVI. Horizontal axis: Date (year-month-day).

Figure 1: Figure panel: (a) Time-series curves before and after S-G filtering. Legend: EVI; S-G EVI. Vertical axes: EVI; S-G EVI. Horizontal axis: Date (year-month-day).

Figure panel: (b) Original EVI data. Scale: 0–30 km. North arrow.

Figure 2: Figure panel: (b) Original EVI data. Scale: 0–30 km. North arrow.

31.52% showed moderate growth, 17.14% showed relatively rapid growth, 2.68% showed significant growth, and only 8.99% showed a decreasing trend, most of which was slight decline (Fig. 3b). Areas with decreasing vegetation coverage in the Hexi Corridor and the Beishan Mountains are mostly located around oases. The interaction between oases and desertification makes the vegetation growth environment around oases relatively complex; in addition, frequent human activities and the arid, water-scarce natural environment in the Hexi Corridor lead to decreased vegetation coverage in the Hexi Corridor and the Beishan Mountains[^31]. The causes of decreased vegetation coverage in the Gannan Plateau are relatively complex; the year-by-year increase in livestock numbers and the impact of free-range cattle and sheep husbandry on the grasslands of the Gannan Plateau

Note: EVI is the enhanced vegetation index; S-G denotes Savitzky-Golay filtering. The same below.

Figure 2 S-G filtering results of EVI from 2001 to 2023

Fig. 2 S-G filtering results of the EVI from 2001 to 2023

The value is relatively large, whereas alpine meadow is one of the main vegetation types on the Gannan Plateau. Therefore, the main factor responsible for the reduction in vegetation cover in this area is human activity, followed by disturbance from climatic anomalies.

The transfer matrix of land-cover types can indicate the directions of increase and decrease in vegetation cover. The results show that, from 2001 to 2023, the area transferred from cultivated land to other land-cover types was 1.65×10^4 km^2 (Table 1), mainly shifting to forest and grassland (Fig. 3e). This indicates that the implementation effects of the project of returning cultivated land to forest and grassland were evident. The outflow area of forest was $6.21 \times$

Figure panel: (c) EVI data after S-G filtering. Scale: 0–30 km. North arrow.

Figure 3: Figure panel: (c) EVI data after S-G filtering. Scale: 0–30 km. North arrow.

10^2 km^2, accounting for a relatively low proportion, and it mainly shifted to cultivated land, shrubland, and grassland. The transfer direction of shrubland was mainly toward grassland and forest. The area transferred from grassland to bare land reached 5.03×10^3 km^2, and the area transferred from grassland to cultivated land was 8.75×10^3 km^2. Meanwhile, the area transferred from bare land to grassland was 8.79×10^3 km^2, and the area transferred to cultivated land was 1.80×10^3 km^2. From 2001 to 2023, conversions of vegetation to other land-cover categories were mainly toward impervious surfaces and bare land, while the conversions of cultivated land to forest and grassland showed the strongest trend of transfer [32].

2.1.2 Spatial stability characteristics of vegetation change

Vegetation change in Gansu Province was generally relatively stable from 2001 to 2023, with coefficients of variation ranging from 0.02 to 2.20. A total of 25.4% of the area showed low-fluctuation change, mainly located in the Gannan Plateau region, the Qinba Mountains region, and the Qilian Mountains region. Most of these areas have primary forests and alpine meadows, and the internal structure of the ecosystems is relatively stable. Areas with relatively low-fluctuation change accounted for 38.9% and were widely distributed across the province. Areas with moderate-fluctuation change accounted for 27.5%, concentrated in the Longdong Loess Plateau region, the Longzhong Loess Hills region, and the Hexi Corridor and Beishan region. Areas with relatively high-fluctuation change and high-fluctuation change were mainly located in the Longzhong Loess Hills region and the Hexi Corridor and Beishan region, accounting for 5.7% and 2.5% of the area, respectively (Fig. 3c).

The high variability of vegetation in the Hexi Corridor and Beishan region is caused by the region' s special natural environment. Under arid natural conditions

(a) Temporal trend of EVI

EVI mean value
Fitted curve

$y = 0.0033x - 6.45$

EVI mean value
Year

(b) EVI change trend

Legend
Vegetation change trend

Slight increase
Moderate increase
Relatively rapid increase
Significant increase

Significant decrease
Relatively rapid decrease
Moderate decrease
Slight decrease
Provincial boundary
Municipal boundary

0 200 km

Proportion/%
Vegetation change trend

(c) Coefficient of variation

Legend
Vegetation variation characteristics

Low fluctuation change
Relatively low fluctuation change
Moderate fluctuation change
Relatively high fluctuation change
High fluctuation change
Provincial boundary
Municipal boundary

0 200 km

5.7%
2.5%
25.4%
38.9%
27.5%

(d) Hurst index

Legend
Persistence of vegetation change

High sustained increase
Relatively high sustained increase
Moderate sustained increase
Slight sustained increase
Weak sustained increase
Slight sustained decrease
Sustained decrease
Provincial boundary
Municipal boundary

0 200 km

1.09%
0.01%

0.8%
9.6%
34.2%
40.0%
14.3%

(e) Changes in land-cover types from 2000 to 2023

Cultivated land
Forest
Grassland
Wetland
Impervious surface
Shrubland
Water bodies
Glaciers and perennial snow
Bare land

Cultivated land
Forest
Grassland
Shrubland
Wetland
Impervious surface
Water bodies
Glaciers and perennial snow
Bare land

Fig. 3 Spatiotemporal characteristics of vegetation and land-use change in Gansu Province

Under such conditions, human production and living activities require a guaranteed normal water supply[^33]. For example, irrigation of farmland in the oasis areas of the Hexi Corridor and the Beishan region is one of the reasons for the artificial allocation of water resources in this area (Fig. 4). These areas where high-fluctuation changes occur are also located in oasis zones. Under the influence of the natural environment, the ecological environment of oasis areas is fragile, and the surrounding desertification is also one of the causes of high-fluctuation changes in these areas[^34]. In the loess hilly region of central Longxi, the high-fluctuation vegetation changes occurring in Lanzhou and Baiyin are influenced by multiple factors, including urbanization and climate.

2.1.3 Analysis of the persistence characteristics of vegetation change

Hurst persistence indicates the persistence of vegetation change. The Hurst index was divided into seven classes.

Table 1 Land cover type transition matrix of Gansu Province from 2001 to 2023 /km^2

Land cover type	Cropland	Forest	Shrubland	Grassland	Water body	Glacier and snow	Bare land	Impervious surface	Wetland	Total	Total outflow
Cropland	41850.13	1877.55	10.01	14143.65	37.32	0.00	128.18	319.27	0.11	58366.22	16516.09
Forest	241.30	33880.02	227.81	151.37	0.30	0.00	0.01	0.62	0.01	34501.44	621.42
Shrubland	29.74	370.01	760.37	505.84	0.07	0.00	0.04	0.00	0.03	1666.1	905.73
Grassland	8740.76	4459.10	288.78	128333.48	126.18	3.40	5034.43	122.64	34.34	147143.11	18809.63
Water body	19.11	0.75	0.00	42.43	422.81	1.72	32.98	7.85	0.04	527.69	104.88
Glacier and snow	0.00	0.03	0.00	4.23	13.44	783.98	224.84	0.00	0.00	1026.52	242.54
Bare land	1796.62	1.37	0.16	8786.81	68.08	94.07	170931.35	28.61	0.03	181707.10	10775.75
Impervious surface	1.50	0.01	0.00	0.25	7.88	0.00	0.12	457.07	0.00	466.83	9.76
Wetland	0.06	2.32	0.00	51.54	2.47	0.00	0.00	0.00	23.95	80.34	56.39

(a) Manufacturing water use

Legend
Water use / 10^6 $m^3 \cdot (30d)^{-1}$
3.20
0.00
—Provincial boundary
—Municipal boundary
0 300 km
N

(b) Agricultural irrigation water use

Legend
Water use / 10^6 $m^3 \cdot (30d)^{-1}$
1.05
0.00
—Provincial boundary
—Municipal boundary
0 300 km
N

(c) Electricity water use

Legend
Water use / 10^6 $m^3 \cdot (30d)^{-1}$
1.07
0.00

–Provincial boundary
–Municipal boundary
0 300 km
N

(d) Domestic water use

Legend
Water use / 10^6 $m^3 \cdot (30d)^{-1}$
0.30
0.00
–Provincial boundary
–Municipal boundary
0 300 km
N

Figure 4 Spatial distributions of water resources utilization in Gansu Province

level (Fig. 3d). In terms of spatial distribution, vegetation overall showed a trend of sustained increase; slight sustained decreases occurred in the Hexi Corridor and the central-western part of the Beishan region, the central part of the Longzhong Loess Hilly Region, and the central part of the Gannan Plateau. Across the province, 1.09% of the area showed a highly sustained increasing trend, 40.0% showed a moderately sustained increasing trend, 9.6% showed a slightly sustained increasing trend, and 34.2% showed a slight sustained increase; these areas were mainly located in the Longdong Loess Plateau, the Longzhong Loess Hilly Region, the Hexi Corridor and Beishan region, and the Qinba Mountains. The proportion of pixels with a relatively high sustained increase was 14.3%, mainly located in the eastern part of the Longdong Loess Plateau, the northern part of the Longzhong Loess Hilly Region, and the Hexi Corridor. Types of sustained decrease accounted for only a small share of the province' s total area; among them, areas of slight sustained recession accounted for 0.8% of the provincial area, while the area of sustained recession was only 0.01%.

This persistent feature in the Longdong Loess Plateau and the Longzhong Loess Hilly Region appears mainly in cultivated land and agricultural land. The Longzhong Loess Hilly Region and the Longdong Loess Plateau have temperatures suitable for vegetation growth; they are winter wheat planting areas in Gansu Province and also produce economic crops such as apples and cherries. Human activities have a positive effect on vegetation change[^35]. Unlike the Longzhong Loess Hilly Region and the Longdong Loess Plateau, the extensive deserts and Gobi in the Hexi Corridor and the Beishan area make the climate dry, precipitation relatively sparse compared with the Longdong Loess Plateau, and, because the bare-soil areas have small heat capacity, surface heat is difficult to store, surface evaporation is high, and the basic conditions for vegetation are poor. This region has artificial oases, dominated by farmland, while the propor-

Fig. 5 Spatial distributions of partial correlation coefficients and significance test of vegetation coverage in Gansu Province with climate factors

Figure 4: Fig. 5 Spatial distributions of partial correlation coefficients and significance test of vegetation coverage in Gansu Province with climate factors

tion of natural oases is small. The terrain in this region is flat and agricultural land is widely distributed; however, constrained by the area of oases and by the encroachment of desertification on oasis boundaries in earlier years, the vegetation there experienced almost no change until the implementation of related ecological protection and management projects, which enabled the oases in the Hexi region to be preserved and developed.

2.2 Correlation between vegetation coverage and climatic factors in Gansu Province

The areas in Gansu Province where vegetation is positively affected by precipitation are mainly located along the southern margin of the Hexi Corridor and Beishan area, in parts of the Longzhong Loess Hilly Region, the Qinba Mountains, and the northern Longdong Loess Plateau (Fig. 5). Areas with negative correlation are mainly located at the eastern and western ends of the Hexi Corridor and Beishan area, the southwestern part of the Gannan Plateau, and local small areas in the central Longzhong Loess Plateau. The greater the precipitation, the higher the vegetation coverage and the better the growth. Temperature has a relatively weak influence on vegetation in Gansu Province, even showing a negative influence. The distribution range of areas where vegetation is negatively correlated with temperature and where no correlation exists is broad (Fig. 5c). Positive correlations occur only in western Zhangye City in the Hexi Corridor and Beishan area, northern Qingyang City in the Longdong Loess Plateau, western Gannan Plateau, and southwestern Longnan City in the Qinba Mountains. Therefore, in vegetation change in Gansu Province, precipitation should occupy the dominant position, primarily promoting vegetation, whereas temperature has little influence on vegetation change in Gansu Province and is mostly negatively correlated, promoting vegetation only in some regions.

The possible reasons for the negative correlation between precipitation and the vegetation correlation coefficient are as follows: under the influence of the underlying surface, soil-type factors lead to soil and water loss; in addition, the vegetation types are grassland and cultivated land with relatively weak soil and water conservation capacity[^35]. When precipitation exceeds the maximum threshold that the underlying surface can withstand, surface runoff increases with precipitation, flow velocity accelerates, erosion of the land surface intensifies, and the environment for vegetation growth is damaged, thereby leading to a negative correlation between precipitation and vegetation growth. The negative correlation between temperature increase and vegetation indicates that, in environments with low precipitation and high surface evaporation,

(a) Partial correlation coefficient between vegetation and precipitation

(b) Significance P-value of the partial correlation coefficient

(c) Partial correlation coefficient between vegetation and temperature

(d) Significance P-value of the partial correlation coefficient

Figure 5. Spatial distributions of partial correlation coefficients and significance test of vegetation coverage in Gansu Province with climate factors

Fig. 5 Spatial distributions of partial correlation coefficients and significance test of vegetation coverage in Gansu Province with climate factors

The rise in temperature intensifies surface evapotranspiration, affecting soil water content and involving agricultural drought; this will lead to reduced chlorophyll in vegetation leaves, closure of leaf stomata, and even withering and death.

2.3 Analysis of the driving factors of vegetation-cover change in Gansu Province

The area proportion of regions lightly promoted by climate factors was the largest (56.96%), located in western Hexi Corridor and the western part of the Beishan region, the eastern part of the Longdong Loess Plateau, the Qinba Mountains, and other areas (Fig. 6a). The significantly promoted regions were located in the central-eastern part of the Hexi Corridor and the Beishan region, the western part of the Gannan Plateau, the Longdong Loess Plateau, the Longzhong Loess Hilly Region, and northern Qinba Mountains, accounting for 12.5%. The area proportion of moderately promoted regions was 19.04%, located in the oasis at the western end of the Hexi Corridor and Beishan region, and the northwestern part of the Longzhong Loess Hilly Region. In the central-western Gannan Plateau and southern Qinba Mountains, climate factors had basically no promoting effect on vegetation change, with an area proportion of 10.07%. The area affected by the inhibitory effect of climate factors was relatively small (1.43%), concentrated in northern Lanzhou and southwestern Wuwei. The influence of human activities on vegetation growth had a complex spatial distribution (Fig. 6b): regions accounting for 75.66% of the province' s vegetated area were not affected by human activities, 6.71% of the area was promoted by human activities, and 17.63% of the area was inhibited by human activities. Regions promoted by human activities were distributed in the Hexi Corridor and Beishan region, the Longzhong Loess Hilly Region, most areas of the Longdong Loess Plateau, and northern Qinba Mountains. Vegetation in the southern Qinba Mountains was slightly inhibited by human activities, and northern Qingyang in the Longdong Loess Plateau was also slightly inhibited by human activities. The region where the influence of human activities was significant and the area was relatively large was the Gannan Plateau.

Climate factors promote vegetation growth through water supply and suitable temperature, while solar radiation is the key to promoting photosynthesis. When precipitation is abundant and the water supply to vegetation root systems is sufficient, vegetation can expand its canopy area through photosynthesis, thereby increasing the leaf area index value; this is the key factor for vegetation to present high coverage. The mechanisms by which human activities promote and inhibit vegetation are relatively complex. Taking the Longzhong Loess Hilly Region and the Longdong Loess Plateau as examples, the promoting effect of human activities on vegetation mostly comes from the relatively large area of cultivated land. In the gullies of the Loess Plateau, villages and cultivated land are widely distributed, and vegetation growth in the above regions is affected by human activities.

(a) Driving effect of climate factors on vegetation change

Legend —Driving type: significant promotion; moderate promotion; slight promotion; basically no promotion; significant inhibition; moderate inhibition; slight inhibition; basically no inhibition; provincial boundary; municipal boundary.

(b) Driving effect of human activities on vegetation change

Legend —Driving type: significant promotion; moderate promotion; slight promotion; basically no promotion; significant inhibition; moderate inhibition; slight inhibition; basically no inhibition; provincial boundary; municipal boundary.

(c) Identification of driving factors of vegetation change by climate factors and human activities

Legend —Identification of driving factors when vegetation decreases: dominated by human activities; dominated by climate; joint effect of climate and human activities. Identification of driving factors when vegetation increases: dominated by human activities; dominated by climate; joint effect of climate and human activities; provincial boundary; municipal boundary.

Fig. 6 Identification of the driving factors of vegetation changes due to climate factors and human activities

The promoting effect is relatively obvious. Similarly, vegetation in the Hexi Corridor and the Beishan area is promoted by both climatic factors and human activities; in parts of the Hexi Corridor, oasis agriculture has reached the level of large-scale irrigation and mechanized management, and crop growth is the main contributor to vegetation greenness in this region[^36-38].

After overlay analysis of the trend of vegetation change, the influence trend of climatic factors, and the influence trend of human activities, vegetation change was divided into two major categories—increase and decrease—and three subcategories: jointly driven by climate and human activities, driven by climatic factors, and driven by human activities. When vegetation increased, the area of vegetation driven by climatic factors accounted for 44.86% of the total vegetated area, the area driven by human activities accounted for 1.29%, and the area under their joint influence accounted for 44.88%. When vegetation decreased, the proportion driven by climatic factors was 8.83%, that driven by human activities was 0.06%, and that jointly driven was 0.08%. In summary, climatic factors are the dominant factor in vegetation change in Gansu Province, followed by human activities. As shown in Fig. 6c, in regions such as the Gannan Plateau and the Hexi Corridor and Beishan area, human activities exert a negative influence on vegetation change.

3 Conclusion

(1) Vegetation in Gansu Province showed an overall increasing trend from 2001 to 2023, with an overall growth rate of $0.0033 \cdot a^{-1}$. The regions showing an increasing trend were the Longdong Loess Plateau, the Longzhong Loess Hilly Region, the Qinba Mountains, and the oasis areas of the Hexi Corridor and Beishan. A decreasing trend in vegetation EVI appeared in the Dunhuang oasis at the western end and the Minqin oasis at the eastern end of the Hexi Corridor and Beishan area, as well as locally in the Gannan Plateau. Across the province, vegetation increase was mainly caused by the conversion of cultivated land to forest and grassland, while vegetation shrinkage was mainly caused by the conversion of grassland to bare land, with relatively small transfer magnitudes.

(2) Precipitation has a positive effect on vegetation growth in Gansu Province, whereas temperature has a negative effect. The area where precipitation is positively correlated with vegetation is relatively large, accounting for 80.11%, and is distributed in the Hexi Corridor and Beishan area, the Longzhong Loess Hilly Region, the Longdong Loess Plateau, and the Qinba Mountains. The area where temperature is negatively correlated with vegetation accounts for 57.24%, mainly located in the eastern section of the Hexi Corridor and Beishan area, the Longzhong Loess Hilly Region, the Longdong Loess Plateau, and parts of the Gannan Plateau.

(3) Climatic factors are the dominant factor in vegetation change in Gansu Province, and their influence on vegetation across the spatial distribution as a whole is mostly promotive. Among them, the obvious promotion areas are located in the southwestern part of the Gannan Plateau, the northern part of the Longzhong Loess Hilly Region, and the southeastern part of the Hexi Corridor and Beishan area; the inhibition areas are concentrated in the northwestern part of Lanzhou City and the southern part of Wuwei City. The spatial distribution of the driving effect of human activities on vegetation in Gansu Province is complex. The Longdong Loess Plateau and the Longzhong Loess Hilly Region are mainly promoted by human activities, and vegetation in the oasis areas of the Hexi Corridor and Beishan region also shows obvious promotion by human activities;

the inhibition areas are mainly located in the Gannan Plateau and in the southern part of the Hexi Corridor and Beishan area, and vegetation in northern Qingyang City on the Longdong Loess Plateau is inhibited by human activities.

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Impacts of climatic factors and human activities on vegetation dynamics in Gansu Province from 2001 to 2023

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Abstract: Gansu Province is an important ecological barrier to western China, with fragile environmental conditions and prominent anthropogenic disturbances. Vegetation is a key indicator of regional ecological status. Analyzing changes in flora in response to climatic factors and human activities is of great significance for understanding the evolution of Gansu Province' s ecology. Enhanced vegetation index, annual precipitation, and annual mean temperature data were statistically analyzed to ascertain the vegetation changes in Gansu Province over the past 24 years and assess the impacts of climate variability and human activities. The results show that: (1) Vegetation in Gansu Province exhibited an overall trend of increase, with an average growth rate of 0.0033 · a^-1; forest and grasslands significantly improved. (2) Vegetation alteration was relatively more stable in eastern Gansu, the Gannan Plateau, and the Qinba Mountains, accounting for 65.2% of the study area, whereas that in central Gansu and the Hexi Corridor, accounting for 35.7%, fluctuated greatly. Overall, vegetation change was dominated by continuous improvement, although some areas within the Gannan Plateau, central Gansu, and the Hexi region exhibited continuous degradation. (3) Climatic factors were the main drivers of such a change. Precipitation was positively correlated with vegetation change in 80.11% of the area, whereas temperature was weakly negatively associated. Anthropogenic activities positively impacted vegetative growth within the Hexi Corridor and in central and eastern Gansu, whereas adversely in some areas of the Gannan Plateau and the Qinba Mountains.

Keywords: vegetation dynamics; climate factors; anthropogenic activities; Gansu Province

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