Analysis of Normalized Difference Vegetation Index Variation and Its Driving Factors in the Shiyang River Basin (Postprint)

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Abstract

The Shiyang River Basin suffers from severe land desertification and has a very fragile ecological environment. Based on monthly NASA GIMMS Normalized Difference Vegetation Index (NDVI), temperature, precipitation, sunshine hours, and evaporation data for the Shiyang River Basin from 2000 to 2020, and employing methods such as trend slope, cumulative anomaly and signal-to-noise ratio, correlation coefficient, and multiple regression, this study analyzes and investigates the changes in vegetation index and its driving factors in the Shiyang River Basin. The results show that: (1) Influenced by altitude, topography, and climate differences, the spatial distribution of NDVI in the Shiyang River Basin follows the pattern: upstream > entire basin > midstream > downstream. (2) The annual NDVI for the entire basin and the upper and middle reaches shows a significant increasing trend, while the lower reach shows a slight increasing trend, with trend slopes following the pattern: upstream > entire basin > midstream > downstream. Seasonal NDVI also exhibits an increasing trend, with summer, autumn, and winter showing basically significant growth. The annual NDVI for the entire basin and the upper, middle, and lower reaches experienced an abrupt change in 2010 or 2011. (3) The climate factors influencing NDVI changes in the Shiyang River Basin are, in order, precipitation, temperature, evaporation, and sunshine hours. NDVI changes in the Shiyang River Basin are driven by both climate change and human activities; climate factors contribute more to NDVI than human activities in the entire basin and upper reaches, while climate factors and human activities contribute comparably in the middle and lower reaches. After the abrupt change, the contribution rate of human activities increased significantly compared with before, while the contribution rate of climate factors was relatively reduced. The research results can provide a scientific basis for vegetation restoration and ecological environment protection in the Shiyang River Basin.

Full Text

Normalized Difference Vegetation Index Change and Its Driving Factors in the Shiyang River Basin

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Abstract

The Shiyang River Basin faces severe land desertification and an extremely fragile ecological environment. Based on monthly NASA GIMMS Normalized Difference Vegetation Index (NDVI) data, along with temperature, precipitation, sunshine duration, and evaporation data from 2000 to 2020, this study analyzed NDVI variation characteristics and driving factors using trend slope analysis, cumulative anomaly and signal-to-noise ratio, correlation coefficients, and multiple regression methods. The results show that: (1) The spatial distribution of NDVI in the Shiyang River Basin follows the pattern of upper reaches > whole basin > middle reaches > lower reaches, influenced by altitude, topography, and climate differences. (2) Annual NDVI showed a significant increasing trend in the whole basin and its upper and middle reaches, with a slight increasing trend in the lower reaches. The trend slopes follow the order: upper reaches > whole basin > middle reaches > lower reaches. Seasonal NDVI also exhibited growth trends, with slope magnitudes in the order: summer > autumn > winter > spring, with summer, autumn, and winter showing basically significant growth. A mutation in annual NDVI occurred around 2010 or 2011 for the whole basin and its upper, middle, and lower reaches. (3) The climate factors affecting NDVI change are precipitation, temperature, evaporation, and sunshine hours. Temperature, precipitation, and evaporation positively contribute to NDVI, while sunshine duration has a negative effect. NDVI change in the Shiyang River Basin results from the combined effects of climate change and human activities. Climate factors contribute more than human activities in the whole basin and upper reaches, while their contributions are comparable in the middle and lower reaches. The contribution rate of human activities increased significantly after the mutation, while that of climate factors relatively weakened. These findings provide a scientific basis for vegetation restoration and ecological protection in the Shiyang River Basin.

Keywords: NDVI; trend slope; driving factor; multiple regression; Shiyang River Basin

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Vegetation, which collectively refers to plant communities covering the Earth's surface, constitutes one of the main components of terrestrial ecosystems. It plays a crucial role in land energy exchange, water cycling, and global biochemical cycles, and is vital for global climate stability and carbon balance. The Normalized Difference Vegetation Index (NDVI) is a remote sensing indicator for studying vegetation coverage and growth conditions, and its variation trends can reflect the degree of vegetation cover change. NDVI serves as an important metric for measuring surface vegetation growth and evaluating regional ecosystem health.

Under global warming, climate change has caused worldwide destruction of ecological environments and biological resources, leading to significant vegetation cover changes in some regions. Studies have shown that vegetation activity in the Northern Hemisphere's mid-to-high latitudes has significantly increased, particularly in Asia and North America between 40°N and 70°N. Domestic research has found that as China's climate shifts from warm-dry to warm-humid conditions, vegetation activity in most regions has shown an enhancing trend, primarily due to advanced or extended plant growing seasons caused by global warming. In addition to climate change, human activities also drive vegetation changes. In recent years, with the implementation of various ecological projects in China, the impact of human activities on vegetation cover change has become increasingly evident. Therefore, human activity impacts must be considered alongside climate change effects in vegetation change research.

The Shiyang River Basin, located in the arid region of northwest China, represents a sensitive zone for climate change and a fragile area for natural ecosystems. It is one of the most densely populated, intensively water-resource-developed, ecologically vulnerable, and severely desertified inland river basins in northwest China's arid region. The basin belongs to both a northwestern oasis and a typical area of the northern agro-pastoral ecotone, with the Minqin desert area in its lower reaches. Vegetation cover changes in this basin affect the ecological civilization construction of the entire region. In recent years, against the backdrop of global warming and the implementation of comprehensive management projects in the Shiyang River Basin, the vegetation environment has undergone certain changes. Therefore, studying the evolution characteristics of NDVI and predicting future vegetation development trends are of great significance for ecological environmental protection in the basin. This paper analyzes NDVI variation trends from 2000 to 2020 and explores the response mechanisms of NDVI changes to climate change and human activities, providing a scientific basis for vegetation restoration and ecological protection in the Shiyang River Basin.

1. Study Area Overview

The Shiyang River Basin is one of the three major inland rivers in the Hexi Corridor of Gansu Province, located in the eastern section of the Hexi Corridor at the northern slope of the Qinghai-Tibet Plateau. It borders the Qilian Mountains to the south, the Tengger and Badain Jaran deserts to the north, and the western edge of the Loess Plateau to the east. The basin covers a total area of 4.16$×10^{4}$ km^2, with geographical coordinates between 101°06 ~104°14 E and 37°10 ~39°24 N. The elevation ranges from 1247 to 4853 m, sloping downward from southeast to northwest. The basin includes Tianzhu and Gulang counties in the upper reaches, Liangzhou District and Yongchang County in the middle reaches, and Minqin County in the lower reaches [Figure 1: see original paper].

Situated at the intersection of the Loess, Qinghai-Tibet, and Mongolian-Xinjiang plateaus, the basin features diverse landforms including glaciers, mountains, highlands, plains, hills, deserts, and gobi. It has a continental temperate arid to semi-arid climate. Due to large elevation differences, vegetation and climate elements show significant spatial variations, with annual precipitation ranging from 120.8 to 431.1 mm, annual temperature from 0.7 to 9.4°C, and annual sunshine duration from 2661.2 to 3184.8 h. Soil types include alpine cold desert soil, alpine meadow soil, subalpine meadow soil, mountain gray-cinnamon soil, mountain chernozem, mountain chestnut soil, mountain valley meadow soil, sierozem, desert sierozem, gray-brown desert soil, takyr soil, aeolian sandy soil, meadow soil, bog soil, solonchak, and irrigated soil. The latest monitoring shows the basin contains various ecosystems including oasis farmland, desert, desert wetland, desert lakes, and sandy desert, with low surface vegetation coverage. The southern Qilian Mountains in the upper reaches have dense forests, grasslands, and shrubs; the middle reaches' irrigated oasis areas have moderate vegetation; while most lower reaches consist of semi-desert, desert, and sandy areas with sparse, stunted plants dominated by drought-resistant shrubs and semi-shrubs, creating an extremely fragile ecological environment. With the advancement of ecological civilization construction and the implementation of the Shiyang River Basin key management project since 2007, vegetation in the basin has shown a gradual recovery trend.

2. Data and Methods

2.1 Data Sources

NDVI data were obtained from the Geospatial Data Cloud platform with 500 m spatial resolution. Monthly temperature, precipitation, sunshine duration, and evaporation data from 2000 to 2020 were collected from five meteorological stations in Minqin County, Liangzhou District, Yongchang County, Gulang County, and Tianzhu County in the Shiyang River Basin. All data series underwent strict quality control and are highly reliable. Basin-wide values represent averages from all five stations, upper reaches values are averages from Tianzhu and Gulang counties, middle reaches values are averages from Liangzhou District and Yongchang County, and lower reaches values are from Minqin County.

2.2 Methods

2.2.1 Trend Analysis A univariate linear regression trend method was used to analyze NDVI change trends, calculated as:

$$x_i = at_i + b$$

where x_i is NDVI in year i; a is the trend slope; t_i is the corresponding time; b is the constant term; and n is the number of study years. Following Song et al.'s trend slope classification and considering actual vegetation changes in the study area, NDVI trends were divided into five grades .

2.2.2 Cumulative Anomaly and Signal-to-Noise Ratio Mutation phenomena represent discontinuities in element changes, commonly identified using cumulative anomaly indicators:

$$C(t) = \sum_{i=1}^{t} (x_i - \bar{x})$$

where $C(t)$ is the cumulative anomaly in year t; x_i is NDVI in year i; and $\bar{x}$ is the mean NDVI for the study period. When $|C(t)|$ reaches its maximum, the corresponding t is the turning year. To test whether the turning point meets mutation criteria, the signal-to-noise ratio for the turning year is calculated:

$$S/N = \frac{|\bar{x}_1 - \bar{x}_2|}{s_1 + s_2}$$

where S/N is the signal-to-noise ratio; $\bar{x}_1$ and $\bar{x}_2$ are the means before and after the turning year; and s_1 and s_2 are the standard deviations before and after the turning year. When $S/N > 1.0$, a mutation phenomenon exists, and the year with maximum S/N is defined as the mutation year.

2.2.3 Correlation Coefficient Method The correlation coefficient method was used to analyze the relationship between NDVI and climate factors. Temperature, precipitation, sunshine duration, and evaporation were selected as closely related factors, calculated as:

$$r_{xy} = \frac{\sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n} (x_i - \bar{x})^2 \sum_{i=1}^{n} (y_i - \bar{y})^2}}$$

where r_{xy} is the correlation coefficient; x_i represents climate factors; y_i represents NDVI; and $\bar{x}$ and $\bar{y}$ are the means of x_i and y_i, respectively.

2.2.4 Multiple Linear Regression Model and Contribution Rate Algorithm Multiple linear regression analysis was performed between NDVI and temperature, precipitation, sunshine duration, and evaporation. The predicted value from the regression model was considered the climate factor influence on NDVI ($NDVI_{NA}$), while residuals (actual remote sensing observations minus predicted values) were considered the human activity influence ($NDVI_{HA}$):

$$NDVI_{NA} = aT + bP + cS + dE + e$$

$$NDVI_{HA} = NDVI - NDVI_{NA}$$

where a, b, c, d, e are model parameters; T, P, S, E represent temperature, precipitation, sunshine duration, and evaporation, respectively; $NDVI_{NA}$ is the climate factor influence value; and $NDVI$ is the measured value.

Following Jin et al.'s criteria for driving factor determination, the contribution rates of climate factors and human activities to NDVI were quantitatively calculated:

$$C_{NA} = \frac{a_{NA}}{a} \times 100\%$$

$$C_{HA} = \frac{a_{HA}}{a} \times 100\%$$

where C_{NA} and C_{HA} are the contribution rates of climate factors and human activities to NDVI, respectively; a_{NA} and a_{HA} are the trend slopes of $NDVI_{NA}$ and $NDVI_{HA}$; and a is the trend slope of actual NDVI.

3. Results

3.1 NDVI Spatial and Temporal Variation Characteristics

3.1.1 Spatial Distribution of NDVI The spatial variation of vegetation coverage in the Shiyang River Basin shows significant differences [Figure 2: see original paper]. The annual average NDVI follows the pattern: upper reaches (0.3513) > whole basin (0.3403) > middle reaches (0.3287) > lower reaches (0.2684). The spatial distribution of maximum and minimum values is basically consistent with the mean distribution, with the maximum in the upper reaches' Tianzhu County and the minimum in the lower reaches' Minqin County. The differences between maximum and minimum values in the upper, middle, and lower reaches range from 0.0246 to 0.0384.

First, NDVI spatial distribution in the Shiyang River Basin is positively correlated with altitude. The correlation coefficients between mean, maximum, and minimum NDVI values and altitude reach 0.7706, 0.8641, and 0.6091, respectively, all passing the significance test at α=0.01, indicating highly significant correlations. Second, NDVI spatial distribution is also related to geographical location and topography. The pattern of upper > middle > lower reaches occurs mainly because the upper reaches are in the southernmost mountainous area with high altitude, forests, and grasslands, resulting in large vegetation coverage and high NDVI. The lower reaches are in the northernmost desert area with more desert and gobi, resulting in small vegetation coverage and low NDVI. The middle reaches are in the central basin section with intermediate altitude and vegetation coverage. Altitude and topography significantly affect NDVI because different elevations and terrains produce different climate factors such as temperature and precipitation, which in turn generate different vegetation types. Therefore, NDVI in the Shiyang River Basin shows distinct regional characteristics due to topographic and climate differences.

3.1.2 Temporal Changes in NDVI From 2000 to 2020, annual NDVI in the Shiyang River Basin showed an increasing trend [Figure 3: see original paper], with trend slopes of $0.0033 \cdot a^{-1}$ for the upper reaches, $0.0024 \cdot a^{-1}$ for the whole basin, $0.0022 \cdot a^{-1}$ for the middle reaches, and $0.0008 \cdot a^{-1}$ for the lower reaches, all passing the significance test at α=0.01. According to , all areas except the lower reaches (slight increase) showed significant increases.

Seasonal NDVI also showed growth trends [Figure 4: see original paper], with slope magnitudes in the order: summer > autumn > winter > spring. Maximum values occurred in summer (upper reaches' Tianzhu County), while minimum values occurred in winter (lower reaches' Minqin County). Seasonal NDVI in Yongchang County, Liangzhou District, and Gulang County in the upper reaches all showed increasing trends. The whole basin and middle reaches showed growth trends in all seasons, with NDVI in all seasons increasing more significantly after 2010. As shown in , seasonal trend slopes in the basin are basically summer > autumn > spring > winter. According to , spring shows moderate increase for the whole basin, significant increase for upper reaches, slight increase for middle reaches, and basically no change for lower reaches; summer shows significant increase for the whole basin and upper/middle reaches, and moderate increase for lower reaches; autumn and winter show significant increase for the whole basin and upper/middle reaches, and slight increase for lower reaches. All seasonal trend slopes passed the significance test at α=0.01.

Using the cumulative anomaly method, mutation analysis of annual NDVI from 2000 to 2020 revealed consistent changes across the whole basin and its upper, middle, and lower reaches [Figure 5: see original paper]. Before 2010, NDVI showed a decreasing trend, while after 2010 it began increasing in the whole basin and lower reaches, and after 2011 in the middle reaches. During the increasing stage after 2010/2011, the signal-to-noise ratios reached maximum values of 2.14 for the whole basin, 1.95 for upper reaches, 1.53 for middle reaches, and 1.86 for lower reaches, all passing the signal-to-noise ratio test (S/N > 1.0). Compared with pre-mutation periods, NDVI increased by 0.0801 for the whole basin, 0.0912 for upper reaches, 0.0746 for middle reaches, and 0.0523 for lower reaches. Therefore, mutations can be considered to have occurred in 2010 for the whole basin and upper/lower reaches, and in 2011 for the middle reaches, with significant vegetation growth after mutation.

3.2 Analysis of Driving Factors

3.2.1 Climate Factors The impact of climate factors on vegetation activity should reflect comprehensive multi-element effects. To analyze climate factor influences on NDVI, correlation analysis selected four closely related climate factors: temperature, precipitation, sunshine duration, and evaporation for multiple regression analysis. To better compare the importance of each factor in the regression equation and eliminate unit effects, all factor values were standardized before multiple linear regression. The regression model was established using Excel's LINEST function, which returns multiple regression statistics including standardized regression coefficients, standard errors, determination coefficients, and residual sum of squares. Significance of standardized regression coefficients was tested using t-tests.

The multiple linear regression models and parameters for $NDVI_{NA}$ are shown in . The multiple correlation coefficients for the Shiyang River Basin regression models are all above 0.85, passing the confidence test at α=0.01 and meeting regression equation accuracy requirements. NDVI is positively correlated with temperature, precipitation, and evaporation, and negatively correlated with sunshine duration in the whole basin and upper/lower reaches. In the middle reaches, NDVI is positively correlated with temperature and precipitation, and negatively correlated with sunshine duration and evaporation. The factors affecting NDVI in the whole basin are, in order: precipitation, temperature, evaporation, and sunshine hours; in the middle reaches: precipitation, temperature, sunshine hours, and evaporation; in the lower reaches: temperature, precipitation, evaporation, and sunshine hours.

The Shiyang River Basin shows a warming and humidifying trend, with significant temperature increases and increasing precipitation and evaporation, while sunshine hours show a decreasing trend. Temperature increases and precipitation/evaporation increases all promote vegetation cover growth, but increased sunshine duration somewhat inhibits vegetation cover growth. Therefore, NDVI can be predicted through forecasting of temperature, precipitation, sunshine duration, and evaporation.

Using the regression model to calculate annual $NDVI_{NA}$ series for the whole basin and its reaches revealed increasing trends from 2000 to 2020 [Figure 6: see original paper], with trend slopes of $0.0020 \cdot \mathrm{a}^{-1}$ for upper reaches, $0.0014 \cdot \mathrm{a}^{-1}$ for whole basin, $0.0011 \cdot \mathrm{a}^{-1}$ for middle reaches, and $0.0004 \cdot \mathrm{a}^{-1}$ for lower reaches, all passing significance tests at α=0.01. According to , all areas except the lower reaches (basically unchanged) showed moderate to significant increases. The contribution rates of climate factors to NDVI, calculated using the trend slopes, are 60.6% for upper reaches, 58.3% for whole basin, 50.0% for middle reaches, and 50.0% for lower reaches .

3.2.2 Human Activities Using the regression model and formula, the annual $NDVI_{HA}$ series affected by human activities in the whole basin and its reaches were obtained, showing increasing trends [Figure 7: see original paper] with trend slopes of $0.0013 \cdot \mathrm{a}^{-1}$ for upper reaches, $0.0010 \cdot \mathrm{a}^{-1}$ for whole basin, $0.0011 \cdot \mathrm{a}^{-1}$ for middle reaches, and $0.0004 \cdot \mathrm{a}^{-1}$ for lower reaches, all passing significance tests at α=0.01. According to , all areas except the lower reaches (basically unchanged) showed moderate increases. The contribution rates of human activities to NDVI, calculated using formula, are 39.4% for upper reaches, 41.7% for whole basin, 50.0% for middle reaches, and 50.0% for lower reaches .

Before 2010, $NDVI_{HA}$ values were mostly negative, with only occasional positive years, while after 2010, $NDVI_{HA}$ values were mostly positive with only occasional negative years, indicating that human activities promoted vegetation growth after the mutation. This aligns with the conclusion that NDVI showed increasing trends after the 2010/2011 mutation.

shows that contribution rates of climate factors and human activities to NDVI differ across the basin. Before the mutation, climate factors contributed significantly more than human activities. After the mutation, the contribution rate of human activities increased significantly while that of climate factors relatively weakened. Overall, climate factors contribute more to NDVI than human activities in the Shiyang River Basin.

4. Discussion

This study analyzed NDVI changes and driving factors in the Shiyang River Basin, which is important for ecological protection. First, the significant increasing NDVI trend is consistent with changes across China and neighboring Xinjiang region. The NDVI mutation around 2010/2011, with obvious vegetation recovery after mutation, aligns with findings by Luo et al., Xu et al., and Ren et al. The increased contribution rate of human activities after mutation likely results from comprehensive management projects implemented since 2007, including water diversion projects, returning farmland to forest and grassland, and mountain closure for grazing prohibition. These effective protection measures have significantly promoted vegetation restoration. In summary, vegetation cover change in the Shiyang River Basin is driven by both climate factors and human activities, with climate factors as the primary driver and human activities as secondary, though their relative contributions vary across reaches.

Second, this study established a multiple regression prediction model between NDVI and climate factors, using residuals to represent human activity impacts, which reduces deviation in climate factor influence values and provides good predictive indication for vegetation cover change. However, this study used data from only five national meteorological stations, which are sparse, unevenly distributed, and coarse-gridded, with limited spatial representation reflecting only basin-average conditions. Therefore, more regional meteorological station data should be collected for more comprehensive and detailed studies of climate factor driving mechanisms to better reveal the actual situation of vegetation change drivers in the Shiyang River Basin.

5. Conclusions

(1) Influenced by altitude, topography, and climate differences, NDVI spatial distribution in the Shiyang River Basin follows the pattern: upper reaches $>$ whole basin $>$ middle reaches $>$ lower reaches. Annual NDVI from 2000 to 2020 showed increasing trends, with trend slopes of $0.0033 \cdot \mathrm{a}^{-1}$ for upper reaches, $0.0024 \cdot \mathrm{a}^{-1}$ for whole basin, $0.0022 \cdot \mathrm{a}^{-1}$ for middle reaches, and $0.0008 \cdot \mathrm{a}^{-1}$ for lower reaches. Except for slight increase in lower reaches, the whole basin and upper/middle reaches showed significant increases. Seasonal NDVI also showed growth trends, with summer, autumn, and winter basically showing significant increases. Annual NDVI mutations occurred in 2010 for the whole basin and upper/lower reaches, and in 2011 for the middle reaches.

(2) Climate factors affecting NDVI change are precipitation, temperature, evaporation, and sunshine hours, in that order of importance. Temperature increases and precipitation/evaporation increases promote vegetation cover growth, while increased sunshine duration somewhat inhibits vegetation cover growth. NDVI change results from combined climate factor and human activity drivers, with climate factors contributing more than human activities in the whole basin and upper reaches, while contributions are comparable in middle and lower reaches. Before mutation, climate factors contributed significantly more than human activities; after mutation, human activity contribution increased significantly while climate factor contribution relatively weakened. This indicates that vegetation cover change in the Shiyang River Basin is driven by both climate factors (primary) and human activities (secondary), with varying contribution rates across reaches.

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