Effects of Climate and Human Activities on Vegetation NPP Change in the Loess Plateau (Postprint)

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Abstract

This study obtained a vegetation NPP dataset for the Loess Plateau from 2000–2018 using the CASA model and quantitatively analyzed the impacts of climate change and human activities on vegetation NPP variation through correlation and residual analysis methods. The results indicate: (1) Vegetation NPP on the Loess Plateau from 2000–2018 exhibited a spatial pattern characterized by high values in the southeast and low values in the northwest; approximately 86.86% of the study area demonstrated an increasing trend in vegetation NPP, primarily in the core zones of the Grain for Green Program; areas exhibiting a decreasing trend accounted for 13.14%, mainly distributed in the arid northwestern regions. (2) The contribution rates of climate change and human activities to vegetation NPP variation were 48.78% and 51.22%, respectively, with pronounced spatial heterogeneity. Vegetation dynamics in sparsely populated and relatively underdeveloped regions were predominantly influenced by climate change, whereas vegetation changes in densely populated and economically developed areas were primarily driven by human activities. (3) As an arid and semi-arid region, vegetation on the Loess Plateau exhibits relatively high sensitivity to climate change. With increasingly frequent human activities, climate and human activities jointly influence vegetation dynamics on the Loess Plateau. This study enhances understanding of the impacts of climate change and human activities on vegetation dynamics and provides a scientific basis for vegetation restoration and high-quality development on the Loess Plateau.

Full Text

Impacts of Climate Change and Human Activities on Vegetation NPP Changes in the Loess Plateau

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Abstract: This study employed the CASA model to generate a net primary productivity (NPP) dataset for the Loess Plateau from 2000 to 2018. Using correlation analysis and residual analysis, we quantitatively assessed the relative contributions of climate change and human activities to vegetation NPP variation. The results revealed a spatial distribution pattern of NPP that was high in the southeast and low in the northwest. Approximately 86.86% of the study area exhibited an increasing NPP trend, primarily concentrated in the core region of the Grain for Green Program, while 13.14% showed a decreasing trend, mainly distributed in the arid northwestern region. The contribution rates of climate change and human activities to vegetation NPP variation were 48.78% and 51.22%, respectively. Climate change dominated vegetation dynamics in sparsely populated and economically underdeveloped areas, whereas human activities were the primary driver in densely populated regions with better economic development. As an arid and semi-arid region, the Loess Plateau' s vegetation demonstrates heightened sensitivity to climate change, with both climate factors and human activities jointly influencing vegetation dynamics. This study enhances understanding of how climate change and human activities affect vegetation dynamics and provides a scientific basis for vegetation restoration and sustainable development in the Loess Plateau.

Keywords: climate change; human activities; residual analysis; Loess Plateau

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1.1 Study Area Overview

The Loess Plateau (107°28 -111°15 E, 35°21 -39°34 N) is located in central China, spanning seven provinces (autonomous regions): Inner Mongolia, Ningxia, Shaanxi, Shanxi, Gansu, Henan, and Qinghai, with a total area of approximately 64$×10^{4}$ km^2. Characterized by high elevations in the west and low elevations in the east, the region belongs to the arid and semi-arid climate zone, with an annual average temperature of 4-14°C and precipitation ranging from 200–800 mm. Due to its dry and rain-scarce climate, deeply gullied topography, loose soil texture, and intensive human disturbance, the Loess Plateau has become the most severely eroded area in China and the primary source of sediment in the Yellow River Basin. To combat the deteriorating ecological environment, large-scale ecological restoration programs such as the Grain for Green Program were initiated in 1999. With the implementation of these ecological protection projects, the region' s ecological environment has shown significant improvement.

1.2 Data Sources and Processing

This study utilized the CASA model developed by Zhu et al. and its model plugin in the ENVI platform to estimate vegetation NPP for the study area. The model requires several datasets: (1) Monthly vegetation index data (SPOT-VEGETATION NDVI) from 2000-2018, obtained from the Resource and Environmental Science and Data Center of the Chinese Academy of Sciences (https://www.resdc.cn/); (2) Vegetation type data from the GLC2000 global land cover project; (3) Monthly average temperature and total precipitation station data from the China Meteorological Data Network (http://data.cma.cn/); and (4) Solar radiation data from the National Tibetan Plateau Scientific Data Center (https://data.tpdc.ac.cn/), specifically the China Regional Surface Meteorological Elements Driven Dataset (1979-2018), which was processed using ANUSPLIN for format conversion and preprocessing to obtain monthly radiation data. DEM data were acquired from the Geospatial Data Cloud (http://www.gscloud.cn). All datasets underwent preprocessing including projection conversion, resampling to 1 km × 1 km resolution, and clipping to the study area boundary, unified to the WGS_{1984}_{Albers} coordinate system.

2.1 CASA Model

The CASA model estimates NPP using the following formula:

$$NPP(x,t) = APAR(x,t) \times \varepsilon(x,t)$$

where $NPP(x,t)$ represents the net primary productivity of pixel x in month t, $APAR(x,t)$ is the absorbed photosynthetically active radiation, and $\varepsilon(x,t)$ is the light use efficiency.

The absorbed photosynthetically active radiation is calculated as:

$$APAR(x,t) = SOL(x,t) \times 0.5 \times FPAR(x,t)$$

where $SOL(x,t)$ is the total solar radiation at pixel x in month t, and $FPAR(x,t)$ is the fraction of absorbed photosynthetically active radiation by the vegetation canopy.

The light use efficiency is determined by:

$$\varepsilon(x,t) = T_{\varepsilon 1}(x,t) \times T_{\varepsilon 2}(x,t) \times W_{\varepsilon}(x,t) \times \varepsilon_{\max}$$

where $T_{\varepsilon 1}(x,t)$ and $T_{\varepsilon 2}(x,t)$ represent the reduction in net primary productivity due to plant physiological limitations under low and high temperature conditions, $W_{\varepsilon}(x,t)$ is the restriction of light use efficiency by water status, and $\varepsilon_{\max}$ is the maximum light use efficiency under ideal conditions.

2.2 Interannual Variation Trend Analysis

We employed a simple linear regression model to calculate the vegetation NPP trend:

$$\text{slope} = \frac{n \times \sum_{i=1}^{n} i \times NPP_i - \sum_{i=1}^{n} i \sum_{i=1}^{n} NPP_i}{n \times \sum_{i=1}^{n} i^2 - (\sum_{i=1}^{n} i)^2}$$

where slope represents the trend rate of NPP change, i is the time variable (integer from 1 to n), and n is the number of years in the study period. A positive slope indicates an increasing trend, while a negative slope indicates a decreasing trend; the larger the absolute value, the faster the change. The significance of the trend was tested using F-test:

$$F = \frac{U}{Q/(n-2)}$$

where U is the regression sum of squares, Q is the error sum of squares, y_i represents the actual NPP value in year i, and $\bar{y}$ is the mean value.

2.3 Correlation Analysis

Correlation analysis reveals relationships between random variables at equivalent status. This study analyzed the relationship between NPP and different climate factors at the pixel level. The Pearson correlation coefficient was 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, n is the sample size, x_i and y_i are the i-th values of variables x and y, and $\bar{x}$ and $\bar{y}$ are their respective means. The correlation coefficient ranges from $[-1, 1]$, with absolute values closer to 1 indicating stronger correlation and values closer to 0 indicating weaker correlation.

2.4 Residual Analysis

In ecological studies, residual analysis quantifies the impacts of climate change and human activities on vegetation variation by establishing regression models. The analysis proceeds in two steps: (1) Using precipitation and temperature time series as independent variables, we fitted a regression model to obtain predicted NPP values (NPP_{CC}), representing the impact of climate change; (2) The residual between observed NPP (NPP_{obs}) and predicted NPP represents the impact of human activities (NPP_{HA}):

$$NPP_{HA} = NPP_{obs} - NPP_{CC}$$

When $NPP_{HA} > 0$, human activities have a positive impact on vegetation NPP; when $NPP_{HA} < 0$, the impact is negative; and when $NPP_{HA} = 0$, there is essentially no impact. The relative contribution rates were calculated as:

$$\text{Climate Contribution} = \frac{|\text{slope}(NPP_{CC})|}{|\text{slope}(NPP_{CC})| + |\text{slope}(NPP_{HA})|} \times 100\%$$

$$\text{Human Activity Contribution} = \frac{|\text{slope}(NPP_{HA})|}{|\text{slope}(NPP_{CC})| + |\text{slope}(NPP_{HA})|} \times 100\%$$

3.1 Spatiotemporal Variation of Vegetation NPP in the Loess Plateau

From 2000 to 2018, vegetation NPP in the Loess Plateau exhibited a spatial pattern of high values in the south and east, and low values in the north and west. High-value areas were mainly distributed in the Guanzhong region in the south and Shanxi Province in the east, reaching maximum values of 350-500 $g \cdot m^{-2} \cdot yr^{-1}$. Low-value areas were primarily located in Inner Mongolia Autonomous Region in the northwest. The mean annual NPP showed considerable interannual variation, ranging from 250-500 $g \cdot m^{-2} \cdot yr^{-1}$, with an overall fluctuating upward trend of 6.32 $g \cdot m^{-2} \cdot yr^{-1}$. We classified NPP values into five intervals: 0-250, 250-500, 500-750, and >750 $g \cdot m^{-2} \cdot yr^{-1}$. The 250-500 $g \cdot m^{-2} \cdot yr^{-1}$ interval accounted for the largest area proportion (40.74-42.73%), though this proportion showed a decreasing trend over time. The area proportion of the 500-750 $g \cdot m^{-2} \cdot yr^{-1}$ interval ranged from 53% to 77%, indicating a slow increase. The >750 $g \cdot m^{-2} \cdot yr^{-1}$ interval accounted for 6-14% of the area, also showing a gradual upward trend.

The linear regression slope of NPP from 2000 to 2018 ranged from -39.44 to 36.55 $g \cdot m^{-2} \cdot yr^{-2}$. Areas with increasing trends accounted for 86.86% of the study region, distributed across most of the Loess Plateau, with extremely significant increases concentrated in northern Shaanxi (Yan' an, Yulin), the Lüliang Mountains in Shanxi (Shuozhou, Xinzhou, Lüliang, Taiyuan), Guyuan in Ningxia, and eastern Gansu (Linxia, Dingxi, Tianshui, Qingyang). Non-significant change areas were mainly distributed in Inner Mongolia (Ordos, Hohhot, Ulanqab), Jinzhong in Shanxi, Ningxia, Gansu (Baiyin, Lanzhou), and Qinghai Province. Decreasing trend areas accounted for 13.14%, scattered in southeastern Henan, the Guanzhong region of Shaanxi, and remote northwestern border areas.

3.2 Impact of Climate Change on Vegetation NPP

The correlation coefficient between annual average temperature and NPP was 0.415, with positive correlations covering 41.5% of the study area, mainly in Yulin (Shaanxi), western Shanxi (Lüliang, Taiyuan, Jinzhong, Xinzhou), Ningxia, and Qinghai. Negative correlations accounted for 58.5%, primarily in Ordos (Inner Mongolia), Shaanxi (Yan' an, Weinan), and Dingxi (Gansu). The correlation coefficient between cumulative precipitation and NPP was 0.621, with positive correlations dominating 93.79% of the region, particularly in Shanxi, northern Shaanxi, Ningxia, and Qinghai. Negative correlations (6.21%) were concentrated in the Guanzhong Plain and southern Henan. Overall, the relationships between NPP and precipitation/temperature showed distinct spatial heterogeneity and complementarity: areas positively correlated with precipitation were often negatively correlated with temperature, and vice versa.

3.3 Impact of Human Activities on Vegetation NPP

Vegetation NPP variation results from the combined effects of climate change and human activities. Based on precipitation and temperature, we first calculated predicted NPP values (NPP_{CC}), then derived the residual (NPP_{HA}) as the impact of human activities. From 2000 to 2018, human activities showed a decreasing trend (negative impact) in 15.75% of the region, mainly in northern Inner Mongolia, the Guanzhong Plain, and parts of Henan. Human activities demonstrated an increasing trend (positive impact) in 84.25% of the area, particularly pronounced in Yan' an and Yulin (northern Shaanxi). The overall impact rate of human activities showed a fluctuating upward trend from negative to positive values, indicating a shift from predominantly negative to positive influences. The negative impact was most notable in 2000-2005, during the initial implementation of the Grain for Green Program when vegetation had not yet established on converted farmland. After 2005, as vegetation recovered and ecological conditions improved, human activities exerted increasingly positive effects.

3.4 Relative Contribution Rates of Climate Change and Human Activities

The relative contributions of climate change and human activities to NPP variation were 48.78% and 51.22%, respectively. Spatially, climate contribution rates were classified into five intervals: 0-20%, 20-40%, 40-60%, 60-80%, and 80-100%. The 40-60% interval covered the largest area (38.85%), followed by 20-40% (32.76%) and 60-80% (17.22%). High climate contribution rates (60-100%) were concentrated in the Hetao Plain and northern/southern Shanxi. Low contribution rates (0-20%) were scattered in southern Gansu, Shaanxi, and Shanxi.

Human activity contribution rates showed a different pattern: the 20-60% interval accounted for the largest area (45.89%), followed by 60-100% (38.85%) and 0-20% (15.26%). High human activity contributions (60-100%) were found in central Shanxi (Lüliang, Linfen), Shaanxi (Yan'an, Baoji), and Qingyang/Pingliang in Gansu. Low contributions (0-20%) were sporadically distributed in border areas.

At the provincial scale, climate contribution rates increased from Gansu (47.98%) < Shaanxi < Henan < Qinghai < Shanxi < Ningxia < Inner Mongolia (64.4%). Human activity contributions were highest in Gansu (52.02%) and Shaanxi (60.35%), and lowest in Inner Mongolia (35.6%). This pattern indicates that climate change dominates vegetation dynamics in sparsely populated, less developed provinces, while human activities are more influential in densely populated, economically developed provinces.

4 Discussion

4.1 Temporal and Spatial Characteristics of Vegetation NPP From 2000 to 2018, vegetation NPP in the Loess Plateau showed large interannual variation but an overall fluctuating upward trend. Following the implementation of the Grain for Green Program in 1999, with the Loess Plateau as a key demonstration area, vegetation gradually recovered and ecological conditions improved substantially, leading to increased NPP. Spatially, the pattern of high NPP in the southeast and low NPP in the northwest reflects the region' s climatic gradient. The increasing trend across 86.86% of the region, particularly in northern Shaanxi and the Lüliang Mountains (the core Grain for Green area), demonstrates the effectiveness of ecological restoration. The decreasing trend in 13.14% of the region, mainly in the arid desert areas of the northwest, aligns with findings from previous studies.

4.2 Mechanisms of Climate Change and Human Activity Impacts Climate change alters vegetation composition, distribution, and growth status as plants adapt to new environmental conditions, particularly in arid and semi-arid regions. Our residual analysis, using temperature and precipitation as key climate factors, revealed that climate change and human activities jointly drove NPP variation with contributions of 48.78% and 51.22%, respectively, consistent with previous research. However, residual analysis has limitations. This study only used temperature and precipitation to represent climate factors, whereas other studies have incorporated solar radiation and more ecologically meaningful climate indices. Future research should optimize climate factor selection to improve model robustness. Additionally, human activities were treated as a single factor without distinguishing between specific drivers such as urban expansion versus ecological restoration. More detailed classification of human activities would reduce uncertainty in attributing vegetation changes.

5 Conclusions

Based on CASA-modeled NPP data and integrated trend, correlation, and residual analyses, we quantified the impacts of climate change and human activities on vegetation NPP in the Loess Plateau. The main conclusions are:

1) From 2000 to 2018, vegetation NPP exhibited a northwest-southeast gradient (high in the southeast, low in the northwest) with an overall fluctuating upward trend. Increasing trends dominated northern Shaanxi and

the Lüliang Mountains (86.86% of the region), while decreasing trends occurred primarily in the arid desert areas of the northwest (13.14%).

2) The relative contributions of climate change and human activities to NPP variation were 48.78% and 51.22%, respectively. Climate change was the dominant factor in the Hetao Plain and northern/southern Shanxi, while human activities were dominant in central Shanxi, northern Shaanxi (Yan' an), and parts of Gansu. At the provincial level, climate contributions increased from Gansu to Inner Mongolia, whereas human activity contributions were highest in Gansu and Shaanxi.

3) As an arid and semi-arid region, the Loess Plateau' s vegetation is highly sensitive to climate change. With the large-scale implementation of the Grain for Green Program, human activities have played an increasingly important role in ecological improvement. This study only considered temperature and precipitation as key climate factors and did not disaggregate specific human activity types. Future research should address these limitations to provide more robust scientific support for regional ecological restoration and management.

References

[1] Yang Huijin, Li Xiaoyu, Liu Lijuan, et al. Estimation of net primary productivity in arid region based on coupling model[J]. Chinese Journal of Applied Ecology, 2016, 27(6): 1750-1758.

[2] Zhao Miaomiao, Liu Yi, Yang Jilin, et al. Spatio-temporal patterns of NPP and its relations to climate in China based on HASM[J]. Ecology and Environmental Sciences, 2019, 28(2): 215-225.

[3] Qu Yingbo, Zhao Yuanyuan, Ding Guodong, et al. Effects of climate and human activities on vegetation cover changes in Xilinguol steppe[J]. Arid Zone Research, 2021, 38(3): 802-811.

[4] Kong D D, Zhang Q, Singh V P, et al. Seasonal vegetation response to climate change in the northern Hemisphere (1982-2013)[J]. Global and Planetary Change, 2017, 148: 1-8.

[5] Chen Shuting, Guo Bing, Yang Fei, et al. Spatio-temporal patterns of NPP and its response to climate change in the Qinghai-Tibet Plateau from 2000 to 2015[J]. Journal of Natural Resources, 2020, 35(10): 2511-2527.

[6] Qin Siguo, Zhong Guohui, Wang Jingsheng. The Influence of climate pattern on grassland NPP and the study on livestock carrying capacity in NagQu[J]. Journal of Arid Land Resources and Environment, 2010, 24(7): 159-164.

[7] Cui Zhenzhen, Ma Chao, Chen Dengkui. Spatiotemporal variation of vegetation in the Horqin Sandy Land and its response to climate change from 1982-2015[J]. Arid Zone Research, 2021, 38(2): 536-544.

[8] Zhang Jie, Pan Xiaoling, Gao Zhiqiang, et al. Satellite estimates and change detection of Net Primary Productivity of oasis-desert based on ecosystem process with remotely sensed forcing in arid western China[J]. Acta Geographica Sinica, 2006, 61(1): 15-25.

[9] Zhu Wenquan, Pan Yaozhong, Zhang Jinshui. Estimation of Net Primary Productivity of Chinese terrestrial vegetation based on remote sensing[J]. Journal of Plant Ecology, 2007, 31(3): 414-424.

[10] Zhu Yingying, Han Lei, Zhao Yonghua, et al. Simulation and spatio-temporal pattern of vegetation NPP in Northwest China[J]. Chinese Journal of Ecology, 2019, 38(6): 1861-1871.

[11] Cui Linli, Du Huaqiang, Shi Jun, et al. Spatial and temporal pattern of vegetation NPP and its relationship with climate in the southeastern China[J]. Scientia Geographica Sinica, 2016, 36(5): 787-793.

[12] Nemani R R, Keeling C D, Hashimoto H, et al. Climate-driven increases in global terrestrial net primary production from 1982 to 1999[J]. Science, 2003, 300(5625): 1560-1563.

[13] Jiao W, Chen Y N, Li W H, et al. Estimation of net primary productivity and its driving factors in the Ili River Valley, China[J]. Journal of Arid Land, 2018, 10(5): 781-793.

[14] Liu Caihong, Wang Pengling, Wen Tingting, et al. Spatio-temporal characteristics of climate change in the Yellow River source area from 1960 to 2019[J]. Arid Zone Research, 2021, 38(2): 293-302.

[15] Zhang Yili, Qi Wei, Zhou Caiping, et al. Spatial and temporal variability in the net primary production (NPP) of alpine grassland on Tibetan Plateau from 1982 to 2009[J]. Acta Geographica Sinica, 2013, 68(9): 1197-1211.

[16] Chemodanov A, Jinjikhashvily G, Habiby O, et al. Net primary productivity, biofuel production and CO_2 emissions reduction potential of *Tetraselmis* sp. (Chlorophyta) biomass in a coastal area of the Eastern Mediterranean[J]. Energy Conversion and Management, 2017, 148: 1497-1507.

[17] Zhang Y, Hu Q W, Zou F L. Spatio-temporal changes of vegetation Net Primary Productivity and its driving factors on the Qinghai-Tibetan Plateau from 2001 to 2017[J]. Remote Sensing, 2021, 13(8): 1487.

[18] Ge W Y, Deng L Q, Wang F, et al. Quantifying the contributions of human activities and climate change to vegetation net primary productivity dynamics in China from 2001 to 2016[J]. Science of Total Environment, 2021, 773: 145648.

[19] Teng M J, Zeng L X, Hu W J, et al. The impacts of climate changes and human activities on net primary productivity vary across an ecotone zone in Northwest China[J]. Science of Total Environment, 2020, 714: 136691.

[20] Feng X M, Fu B J, Piao S L, et al. Revegetation in China' s Loess Plateau is approaching sustainable water resource limits[J]. Nature Climate Change, 2016,

6(11): 1019-1022.

[21] Li G, Sun S B, Han J C, et al. Impacts of Chinese grain for green program and climate change on vegetation in the Loess Plateau during 1982-2015[J]. Science of Total Environment, 2019, 660: 1019-1029.

[22] Liu F, Yan H M, Gu F X, et al. Net Primary Productivity increased on the Loess Plateau following implementation of the Grain to Green Program[J]. Journal of Resources and Ecology, 2017, 8(4): 410-421.

[23] Bryan B A, Gao L, Ye Y Q, et al. China' s response to a national system sustainability emergency[J]. Nature, 2018, 559(7713): 193-204.

[24] Zhang Jiang, Yuan Minshu, Zhang Jing, et al. Responses of the NDVI of alpine grasslands on the Qinghai-Tibetan Plateau to climate change and human activities over the last 30 years[J]. Acta Ecologica Sinica, 2020, 40(18): 6269-6281.

[25] Han Dandan, Mu Xingmin, Gao Peng, et al. Dynamic changes of vegetation in Loess Plateau and its response to extreme climate[J]. Bulletin of Soil and Water Conservation, 2020, 40(2): 247-254.

[26] Cheng Xiaoxin, He Yuanmei, Zhang Yan. Correlations between vegetation restoration and regional climate change in the Loess Plateau[J]. Science of Soil and Water Conservation, 2018, 16(4): 25-33.

[27] Ma Zhuguo, Fu Congbin, Zhou Tianjun, et al. Status and ponder of climate and hydrology changes in the Yellow River Basin[J]. Bulletin of Chinese Academy of Sciences, 2020, 35(1): 52-60.

[28] Xiu Lina, Yan Changzhen, Qian Dawen, et al. Analysis of spatial-temporal change and driving forces of vegetation in Loess Plateau under background of ecological engineering[J]. Bulletin of Soil and Water Conservation, 2019, 39(4): 214-221.

[29] Yin L C, Feng X M, Fu B J, et al. Irrigation water consumption of irrigated cropland and its dominant factor in China from 1982 to 2015[J]. Advances in Water Resources, 2020, 143: 103661.

[30] Sun Y L, Yang Y L, Zhang L, et al. The relative roles of climate variations and human activities in vegetation change in North China[J]. Physics and Chemistry of the Earth, 2015, 87-88: 67-78.

[31] Gang C C, Zhao W, Zhao T, et al. The impacts of land conversion and management measures on the grassland net primary productivity over the Loess Plateau, northern China[J]. Science of Total Environment, 2018, 645: 827-836.

[32] Zheng K, Wei J Z, Pei J Y, et al. Impacts of climate change and human activities on grassland vegetation variation in the Chinese Loess Plateau[J]. Science of Total Environment, 2019, 660: 236-243.

[33] Li J J, Peng S Z, Li Z. Detecting and attributing vegetation changes on China' s Loess Plateau[J]. Agricultural and Forest Meteorology, 2017, 247: 260-270.

[34] Ji Panpan, Gao Minhua, Yang Xiaodong. Analysis of NPP driving force in an arid region of Northwest China: A case study in Yili Valley and parts of Tianshan Mountains, Xinjiang, China[J]. Acta Ecologica Sinica, 2019, 39(3): 2995-3006.

[35] Shi S Y, Yu J J, Wang F, et al. Quantitative contributions of climate change and human activities to vegetation changes over multiple time scales on the Loess Plateau[J]. Science of Total Environment, 2021, 755(2): 142419.

[36] Wang Y Q, Shao M A, Liu Z P, et al. Investigation of factors controlling the regional scale distribution of dried soil layers under forestland on the Loess Plateau, China[J]. Surveys in Geophysics, 2019, 39(4): 214-221.

[37] Dai Zijun, Zhao Xia, Li Guanwen, et al. Spatial-temporal variations in NDVI in vegetation growing season in Qinghai based on GIMMS NDVI 3g.v1 in past 34 years[J]. Pratacultural Science, 2018, 35(4): 713-725.

[38] Zhu Wenquan, Pan Yaozhong, Long Zhonghua, et al. Estimating Net Primary Productivity of terrestrial vegetation based on GIS and RS: A case study in Inner Mongolia, China[J]. National Remote Sensing Bulletin, 2005, 20(3): 300-307.

[39] Yi Lang, Ren Zhiyuan, Zhang Chong, et al. Vegetation cover, climate and human activities on the Loess Plateau[J]. Resources Science, 2014, 36(1): 166-174.