Spatiotemporal variations in vegetation cover on the Loess Plateau, China, between 1982 and 2013: possible causes and potential impacts

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Title:

SPATIOTEMPORAL VARIATIONS IN VEGETATION COVER ON THE LOESS PLATEAU, CHINA, BETWEEN 1982 AND 2013: POSSIBLE CAUSES AND POTENTIAL IMPACTS

Short title:

VARIATIONS IN VEGETATION COVER ON THE LOESS PLATEAU

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ABSTRACT

Soil erosion greatly affects the Loess Plateau of China, limiting local agricultural productivity and leading to severe sedimentation in the Lower Yellow River. As a key component of both natural and anthropogenic ecosystems, vegetation cover plays an important role in controlling soil erosion. The satellite-derived Normalized Difference Vegetation Index (NDVI) is an important indicator of terrestrial vegetation growth. The present study uses a multiyear NDVI dataset (1982–2013) and corresponding datasets of observed climatic variables to analyze changes in NDVI at both temporal and spatial scales using the Mann-Kendall test and a linear regression-based time-lag detection method. Relationships are also investigated between NDVI, climate variations, and human activities (such as afforestation and planting grasses). It is found that the annual average NDVI exhibits an upward trend over the 32-year study period, which is pronounced at the middle of the Loess Plateau. NDVI variations lag behind monthly temperature changes by approximately one month. The contribution of human activities to variations in NDVI has become more significant in recent years, with human activities responsible for 30.4% of the change in NDVI during the period 2001–2013. Increased vegetation coverage has reduced soil erosion at the Loess Plateau in recent years, and hence lowered the sediment load in the middle and lower reaches of the Yellow River. Natural restoration of vegetation appears to be the most effective erosion control measure; it is therefore recommended that engineering measures (such as terracing, check dams, aerial seeding, and irrigation systems) which promote vegetation restoration should feature in the future governance of the Loess Plateau.

KEYWORDS: NDVI; Loess Plateau; Soil erosion; Climate variations; Human activities;

INTRODUCTION

Vegetation acts as a connection between soil, water, and the atmosphere, and is an important indicator of changes in climate and human activities (Vereecken et al., 2010). In an ecosystem, the ground cover provided by vegetation plays a pivotal role in the regulation of various biogeochemical cycles, e.g. water (Gerten et al., 2004; Scheffer et al., 2005; Troch et al., 2009) and carbon dioxide (Allen et al., 1987; Levis et al., 2000). At continental scale, land–atmosphere exchanges of energy and water result in positive feedback between vegetation density and climate, especially in semi-arid zones (Dekker et al., 2007; Zeng et al., 1999). Variations in vegetation growth related to either human activities or climate variations can induce natural disturbances as well as modify biosphere–atmosphere interactions, including the hydrological cycle (Liang et al., 2015; Gao et al., 2016; Wu et al., 2017) and energy budgets (Chapin et al., 2005; McVicar et al., 2007). A lack of protective vegetation can easily trigger severe erosion (Cantón et al., 2001; Ludwig et al., 2005) and subsequent deterioration of the soil (Marques et al., 2008; Gómez et al., 2014; Rodrigo Comino et al., 2017), decline in land productivity (Pimentel and Kounang, 1998; Lantican et al., 2003), and degradation of streams, lakes, and estuaries by transported sediments and pollutants (Zhang et al., 2008; Ouyang et al., 2009, 2010; Tang et al., 2011).

The Loess Plateau in northern China is vegetation deficient, primarily because of inappropriate land use. Low vegetation cover has exacerbated soil loss from the Loess Plateau leading to low agricultural productivity. With a mean denudation rate of 3.0 ± 1.2 mm y^{-1} km^{-2} (Yue et al., 2016), the Loess Plateau supplies ~90% of the sediment in the Yellow River, leading to the well-known “hanging river” phenomenon in the lower reaches (Tang et al., 1991; Kong et al., 2015). For example, at Kaifeng in Henan province, the bed of the Yellow River is elevated approximately 10 m above street level (Miao et al., 2016). The climate of the Loess Plateau is arid and semi-arid, meaning that climate change, and especially changes in precipitation, directly influence vegetation cover (Zhang et al., 2012; Liu & Sang, 2013). Ambient temperature is believed to control seasonal changes in vegetation growth on the Loess Plateau (Xin et al., 2008). Sun et al. (2015) reported that higher temperatures promote growth of vegetation in areas that are less water-stressed. The relationship between vegetation and precipitation on the plateau has been studied extensively (Wang et al., 2010a). Human activity is another very important factor that can influence vegetation growth. To mitigate soil erosion, a series of programs to control water and soil loss have been implemented on the plateau since the 1980s. These particular human activities were designed to improve vegetation coverage. However, other human activities such as regional urbanization and industrialization, overgrazing, logging, and excessive reclamation and mining have resulted in adverse effects on vegetation growth on the Loess Plateau because of their unsustainable use of water resources (Feng et al., 2016). While human activities have played a major role in land-use changes on the Loess Plateau, it is believed likely that the change in vegetation growth may have been accelerated by climate change (Li et al., 2016). Being rather complicated, the overall impact of human activities on the Loess Plateau remains to be fully assessed. Although many previous studies have considered the impacts of climate change and human activities on vegetation cover and ecological restoration of the Loess Plateau (Xin et al., 2008; Li et al., 2013; Lang et al., 2014), the majority have focused on purely qualitative evaluations of the effects of climate change or human activities on variations in the Normalized Difference Vegetation Index (NDVI), and did not take into account time-lag effects.

With this in mind, the present study aims to provide a quantitative overview of vegetation cover in the Loess Plateau, which can be used to guide future works on ecological rehabilitation in this region. The study has the following objectives: i) to analyze variations in the vegetation cover of the Loess Plateau using NDVI time-series data; ii) to investigate time-lag effects of vegetation response to climate factors; and iii) to quantify contributions from climate change and human activities to changes in vegetation cover. The paper is structured as follows: Section 2 outlines the data sources and the analysis methodology; Section 3 presents the key results; and Section 4 lists the main conclusions and recommendations.

DATASETS AND METHODS

2.1 Study area

Lying roughly within 101° – 114° E and 34° – 42° N, the Loess Plateau covers an area of more than 620,000 km^2 of north-central China (Fig. 1), and overlaps the middle reaches of the Yellow River. The Loess Plateau is affected by the typical continental monsoon climate with rainfall concentrated from July to September inclusive, accounting for 60 to 80% of annual precipitation. The surface of the plateau is covered by highly erodible loess layers of average depth 100 m. From the northwest to southeast of the plateau, the surface soil type varies in order of Eolian sand, sandy loess, typical loess and clayey loess (Xie et al., 2016) and the natural vegetation type varies from arid desert to steppe and then to broad-leaf deciduous forest (Sun et al., 2014). Throughout the Loess Plateau, most of the hillsides and native grasslands have been converted to farmland following population growth. The combined effects of frequent heavy rainfalls during the summer months, the high erodibility of loess soil~~,~~ and low vegetation cover have made the Loess Plateau one of the most severely eroded areas in the world. This severe soil erosion has had a significant impact on the ecological security of the Yellow River and on the ecological environment of the Loess Plateau.

Since the 1980s, China has implemented a series of programs to control soil and water loss by optimizing land-use structure and spatial configuration, terracing slopes, converting slope cropland into forest and grassland, enclosing hillsides to remove grazing, building reservoirs, and improving basic farmland practices (Yang, 2003; Miao et al., 2011; Fan et al., 2015a; 2015b; Wang et al., 2015). In 1999, an ecological rehabilitation program called the “Grain-to-Green” Project was extensively implemented on the Loess Plateau. Many infrastructure reforms and ecological projects were undertaken, including the construction of large reservoirs and silt dams, afforestation, conversion of cropland on steep slopes to forest and grassland, and restoration of the biological soil crust. By 2006, about 49% of eroded land on the plateau was subject to these types of soil and water conservation measures (including 52,729 km^2 of prime farmland, 94,613 km^2 of afforestation, and 34,938 km^2 of grass planting) (Gao et al., 2011).

2.2 Data sources

The Normalized Difference Vegetation Index (NDVI), defined as the ratio of the difference between near-infrared reflectance and red visible reflectance to their sum, is an indicator of vegetation greenness and productivity (Tucker, 1979). NDVI has been widely used to describe vegetation dynamics because of its close correlation with biophysical and biochemical variables, such as vegetation coverage (Sun et al., 2015; Zhang et al., 2016). In this study, we consider the long time-series NDVI dataset from the Global Inventory Monitoring and Modeling Systems (GIMMS3g) for the period from January 1982 to December 2013, acquired from the National Oceanographic and Atmospheric Administration (NOAA) (http://ecocast.arc.nasa.gov/data/pub/gimms) (Tucker et al., 2005). The data are at 15-day intervals with a spatial resolution of 0.083° (Fensholt & Proud, 2012). Given that the GIMMS NDVI systematically underestimates vegetation on the Loess Plateau (by up to 0.05) (Sun et al., 2015) we used the MODIS dataset from February 2000 to December 2013 to correct the GIMMS3g dataset and enhance its accuracy and reliability as follows. First, we used linear regression to assess the relationship between the GIMMS3g and MODIS datasets using data from February 2000 to December 2013 for each grid-point in the two datasets. Then, we reconstructed all the temporal data at each grid point over the period from January 1982 to December 2013. (It should be noted that this correction method has been applied successfully in other studies, such as by Zhang et al., 2016). GIMMS3g and MODIS NDVI composites were created using the Maximum Value Composite (MVC) technique, which minimizes the effects of cloud cover by selecting the highest NDVI at each pixel from daily images taken over a period of 15 or 16 days (Holben, 1986).

Observed monthly precipitation and temperature datasets were supplied by the National Meteorological Information Center of the China Meteorological Administration (http://data.cma.cn). The datasets were constructed from approximately 2400 station observations across China, including 299 stations located on the Loess Plateau (Fig.1). The resulting high-density datasets ensure the reliability of the present analysis. For consistency with the NDVI data, we used linear interpolation in MatLab(R) to transform the precipitation and temperature data to a 0.083° × 0.083° grid for the period 1982–2013.

Two detailed national soil erosion surveys were undertaken in China during the periods 1995–1996 and 2010–2012. The soil erosion data were obtained from (http://cese.pku.edu.cn/chinaerosion/) provided by Yue et al. (2016). The national soil erosion survey was conducted with a county as a unit survey area, and included a total of 348 counties across the Loess Plateau.

2.3 Methodology

Trend detection

The statistical significance of the trends in NDVI, precipitation, and temperature was assessed using the nonparametric Mann–Kendall test (Mann, 1945) in MatLab(R), and trend magnitudes were computed by Sen's slope estimator (Sen, 1968). The rank-based nonparametric Mann–Kendall test is more frequently applied than parametric statistical tests to analyses of hydrometeorological time series (Yue et al., 2002) and makes no assumptions about the probability distribution (Önöz & Bayazit, 2003). This method can examine trends in a time series without requiring normality or linearity. Mutation analysis was conducted with a sequential Mann–Kendall test, which involves sequential progressive (*U(t)*) and backward (*U'(t)*) analyses based on the Mann–Kendall test. If the two series cross and then diverge from each other as time progresses, the initial divergence year marks an abrupt turning point in the trend (Mohsin and Gough, 2010; Tabari et al., 2011). The sequential behavior fluctuates close to zero. Detailed descriptions of the Mann–Kendall and sequential Mann–Kendall tests are given by Partal & Kahya (2006) and Sayemuzzaman et al. (2014).

Time-lag detection

The relationship between the NDVI and the climatic factors is given by:

$$Z = k_i \times V + b \tag{1}$$

where k_i is the regression coefficient with a time lag of i months, Z is the NDVI time series (1982–2013), and V is the time series of precipitation or temperature, with a time lag of i. For each climatic factor, the lag month (i) that has the highest coefficient of determination (R^2) is the optimum time lag for the vegetation response (to the given climatic factor).

Quantitative assessment of the impact of climate change and human activities on NDVI variations

Briefly, variations in the NDVI result from climate change, human activities, and other natural factors such as plant diseases, insect herbivory, or wildfire. Assuming that the effects of climate change, human activities, and other natural factors on NDVI are independent, the total change in NDVI ($\Delta NDVI_{total}$) can be expressed as:

$$\Delta NDVI_{total} = \Delta NDVI_{climate} + \Delta NDVI_{human} + \Delta NDVI_{natural\ factors} \tag{2}$$

where $\Delta NDVI_{climate}$ represents the change in NDVI caused by climate change, mainly by precipitation and temperature; $\Delta NDVI_{human}$ represents the change in NDVI caused by human activities, including optimizing the land use structure, terracing slopes, converting slope cropland into forest and grassland, enclosing hillsides to remove grazing, building reservoirs, and improving basic farmland practices; and $\Delta NDVI_{natural\ factors}$ represents the change in NDVI caused by other natural factors.

To quantify the influence of different drivers on NDVI variations, a baseline (benchmark) period is set. Usually, the period during which one individual factor dominates the impact is selected as the baseline period. Here, climate change dominated the impact during the baseline period, with negligible effect arising from human activities (Wu et al., 2017). The relationship between NDVI and climate factors during the baseline period is determined by multiple linear regression analysis.

The NDVI during the post-baseline period is then reconstructed on the basis of the above multiple linear regression. Variation in the reconstructed NDVI is affected solely by climate change. According to Equation (2), any differences between the observed and reconstructed NDVI can be attributed to human activities and other natural factors. Thus, the contributions of climate change ($C_{climate}$) and human activities (C_{human}) and other natural factors ($C_{natural\ factors}$) to variations in NDVI can be calculated from:

$$C_{climate} = \frac{x_{reconstruction} - x_{baseline}}{x_{observation} - x_{baseline}} \times 100\% \tag{3}$$

and

$$C_{human} + C_{natural\ factors} = 100\% - C_{climate} \tag{4}$$

where $x_{\text{observation}}$ represents the mean annual observed NDVI during the post-baseline period, $x_{\text{reconstruction}}$ represents the mean reconstructed annual NDVI during the post-baseline period, and x_{baseline} represents the mean annual NDVI during the baseline period. This process is shown schematically in Fig. 2. We have used similar application of this method in our previous studies (Miao et al., 2011; Kong et al., 2016).

Compared with the impacts of climate change and human activities, the impact of other natural factors on NDVI variations has been very weak throughout the Loess Plateau. Moreover according to local government yearbooks, the states of other natural factors did not change significantly during the past five decades, meaning that their influence on NDVI variations during the post-baseline period can be regarded as the same as during the baseline period. Accordingly, the contribution of other natural factors was taken to be zero in equation (4), as was also the case in previous studies of Loess Plateau (Xin et al., 2007; Li et al., 2013; Li et al., 2015).

RESULTS

3.1 Temporal variations in vegetation cover

The magnitude of the monthly average NDVI and how it changes over time are important indicators of the monthly contribution of vegetation activity to total annual plant growth. Fig. 3 presents the monthly and annual average NDVI time series for the Loess Plateau over the period 1982–2013. The monthly average NDVI fluctuated seasonally, with highest values occurring between July and August and the lowest values occurring between January and February, indicating that vegetation cover was dependent on climate over the 32-year study period. An upward trend is evident in the annual average NDVI (Table 1; Z = 3.91). However, the monthly NDVI variation trends are not consistent, as can be seen in Table 1. For January–March, the monthly NDVI trends are negative but exhibit non-significant Z values in the Mann–Kendall test. For April–October, significant upward trends occurred in NDVI, with a peak rate in October of 0.002 NDVI units per year.

3.2 Spatial variations in vegetation cover

To examine variations in vegetation cover across the Loess Plateau, owing to its complicated climate, NDVI contours extracted by ArcGIS 10.0 are now examined. Fig. 4 shows spatial changes in NDVI averaged over four intervals covering the overall study period from 1982 to 2013. There is greater vegetation cover in the southeast of the plateau than in the northwest. The NDVI = 0.3 contour (blue) did not change significantly between 1982 and 2013. However, the NDVI = 0.2 contour (red) retreated toward the northwest in 2008–2013, compared with the previous time period 1982–2007. This retreat is associated with substantial changes to vegetation cover in the middle of the Loess Plateau. Fig. 5 illustrates the spatial distribution of changes in annual average NVDI throughout the plateau between 1982 and 2013. Although there was an overall upward trend in the annual average NDVI at the scale of the whole study area, there was also a high degree of spatial heterogeneity. As shown in Fig. 5, the annual average NDVI increased in most areas, especially in the middle, south, and north-east of the plateau, but decreased sharply in marginal areas in the west of the plateau.

3.3 Impact of climate change on vegetation coverage

Table 1 summarizes the results of the Mann–Kendall test for trends in precipitation and temperature on the Loess Plateau. Fig. S1 shows the temporal variations in annual precipitation and average temperature over the period 1982–2013. Precipitation increased in certain months and decreased in other months and, overall, there was a non-significant upward trend (0.4603 mm yr^{-1}) in annual precipitation over the study period (1982–2013). An upward trend occurred in temperature in all months (Table 1), with an annual rate of increase of 0.0440^{o}C yr^{-1}, which was significant at the 95% confidence level. The concurrent increases in summer rainfall and temperature would have enhanced plant growth on the plateau.

Fig. 6 shows the monthly precipitation, temperature, and NDVI averaged over the period 1982-2013. The results are plotted month by month and displayed in a stacked fashion to indicate the coupling between NDVI and climatic drivers. It can be seen that the pattern of mean monthly precipitation and temperature values was consistent with changes in NDVI: high values in summer and low values in winter. Fig. 6(c) shows that NDVI increased sharply from April to May and declined steeply from September to October. The peak value of mean NVDI occurred in August, whereas the maximum values of mean precipitation and temperature occurred in July, indicating a time lag in NDVI response to climate factors. Such a time-lag effect has also been reported in previous studies (Wu et al., 2015); the present study investigates the scale of this time lag.

To evaluate the dependency of vegetation cover on temperature and precipitation at different time lags, the temperature and precipitation data were designated as independent variables and the NDVI data as the dependent variable. Given that previous studies at the monthly scale found that the time lag of vegetation responses to climate was generally shorter than three months (Anderson et al., 2010; Chen et al., 2014), we consider time lags in the range 0–3 months. Fig. 7 shows the spatial distributions of time lags between NDVI and the climatic factors, temperature and precipitation, over the plateau. Here the NDVI response invariably lags the driving climatic factors by no more than one month. Comparison between Fig. 7a and Fig. 7b indicates that the time lag of the vegetation response was different for different climatic factors. Vegetation growth showed the greatest correlation with precipitation within the same month and exhibited almost no lag effects over most of the plateau. Grid locations with a 0-month time lag accounted for 66.1 % of the entire study region; the remaining grid locations had a 1-month time lag. For temperature, grid locations with a 0-month time-lag accounted for 36.1 % of the study region, with 1-month time-lags occurring over 63.9 % of the plateau. As shown in Fig. 7, the time lags between NDVI and the climatic factors were different in different regions of the plateau. This may be due to differences in vegetation cover, as reported previously (Wu et al., 2015).

3.4 Impact of human activities on vegetation coverage

Soil conservation projects on the Loess Plateau have predominantly focused on re-vegetation. Until the late 1990s, planting of trees and grasses was the primary approach taken to re-vegetation, but most of the planting attempts were unsuccessful. The planted trees and grasses grew well over the first few years but then began to die because of the formation of a dry layer in the soil (Ping et al., 2013). Climate change dominated the impact on NDVI variations during that period, with negligible influence from human activities. Thus, we select 1982–1990 as the baseline period, and compare the different contributions of climate change and human activities to the spatiotemporal variations in NDVI with respect to the baseline period. The comparison is undertaken separately for the growing season (May to September) and the non-growing season (October to April), noting that the dependence of vegetation cover on climate factors varies between the two seasons. The relationship between NDVI and the climate factors during the baseline period is presented in Fig. S2, which confirms that the multiple linear regression models were acceptable. The annual NDVI data series for the period 1991–2013 was reconstructed on the basis of these two models. Table S1 lists the quantitative results. During the period 1991–2013, the overall contribution of climate change to variations in NDVI was 75.4%, whereas that from human activities was lower at 24.6%. However, during the initial period 1991–2000, climate change played a dominant role, making a 97.3 % contribution. During the later period 2001–2013, the contribution from human activities increased significantly to 30.4% while the contribution from climate change decreased to 69.6%. This is consistent with previous studies which found that soil-conservation projects that included re-vegetation became effective from the late 1990s (Ping et al., 2013; Li et al, 2016). Our results indicate that human activities have had a net positive impact on the restoration of vegetation on the Loess Plateau, in keeping with previous findings~~results~~ (Lang et al., 2014).

3.5 Influence of vegetation cover on soil retention

The Loess Plateau is famous for its deep loess deposits. Relatively high degrees of vegetation cover are found in the mountainous areas and the agricultural areas (the valley plain) in the southern region of the plateau (e.g. the Weihe and Fenhe plains). Less-dense vegetation is found in the loess hilly and gully regions, which have been subject to severe soil erosion (e.g. the Mu Us Desert) (Fig. 4). Restoration of vegetation has mainly occurred in areas of the plateau dominated by water erosion (Fu et al., 2011); and so wind erosion has not been included in the present assessment. According to the Second National Soil Erosion Survey, over 25.7 % of the Loess Plateau suffers from water-induced soil erosion to a moderate or higher degree.

Fig. 8 shows the spatial distribution of water-induced soil erosion throughout the Loess Plateau according to national surveys conducted in 1995–1996 and 2010–2012. All regions on the plateau have suffered from water erosion to varying degrees. Fig. 8a shows that the area with the most severe soil erosion (greater than 8 Mt yr^{-1}) lies in the region between the Toudaoguai and Longmen stations (Zhao et al., 2016) called the coarse sandy hilly catchments area (Zhang et al., 2008). This region covers an area of 7.86×10^4 km^2, accounting for only 14.8% of the entire Yellow River basin but producing nearly 80% of the coarse sediment input to the Yellow River (Xu et al., 1998). A comparison of the difference in soil erosion between the two periods considered (Fig. 8c) shows that the rate of soil erosion has declined in most areas (82%), with worsening erosion present in only a few areas at the margins of the plateau (18%). This is consistent with the spatial variation in vegetation cover on the Loess Plateau described previously. Taking the cases where soil erosion reduced (worsened) while the NDVI increased (decreased) as being consistent, it is found that 70.2% of the total area passes the consistency criteria (Fig. S3~~Fig. S3~~). We again find that the region with the highest degree of improvement in NDVI corresponds to those areas which suffered the greatest degree of erosion during the period 1995–1996 (Fig. 5~~Figure 5~~ and Fig. 8b~~Figure 8b~~).

To better understand the effects of vegetation coverage on erosion, long-term data on the sediment load at the Tongguan and Huayuankou hydrological stations were examined for different soil-conservation periods (Fig. 9). Overall, between 1982 and 2013, the average annual sediment load exhibited a downward trend at both stations. During this period, a significant reduction in sediment load occurred, corresponding to increased vegetation coverage of the Loess Plateau. Our analysis shows that sediment load at Tongguan hydrological station was negatively correlated with vegetation coverage; the correlation coefficient of –0.49 is significant at the 95% confidence level.

DISCUSSION

Based on the foregoing quantitative analysis~~ results~~, it can be inferred that the majority of afforestation projects before the late 1990s did not achieve their goals. Although re-vegetation measures were implemented over several decades beforehand, climate change remained the dominant factor influencing vegetation cover until 2000. It is worth noting that Xin et al. (2008) observed that the benefits from implementation of the large-scale re-vegetation policy continued until the early 21st Century, during which time the annual maximum NDVI kept increasing even when precipitation fell below the annual mean level. Li et al (2016) found that vegetation cover exhibited higher correlation to precipitation and temperature during 1980–1999 compared to 1999–2010 while rates of vegetation growth were higher during 1999–2010 compared to 1980–1999. This also indicated that the re-vegetation projects implemented after 1999 had significant impact on vegetation restoration, in accordance with the present findings. The planting of inappropriate vegetation species appears to have been the main reason why the re-vegetation projects undertaken before the late 1990s were unsuccessful.

Too much emphasis was placed on the economic benefits of afforestation during its initial implementation, leading to a large proportion of non-natural forest with weak ecological functionality being planted (Zhang & Liu, 2007). Several programs within the later phases of the Grain-to-Green project, such as in Wuqi County in northern Shaanxi Province, have demonstrated success with natural re-vegetation, which is now considered the most suitable method for control of soil erosion and ecological restoration (König et al., 2014; Kou et al., 2016; Sun et al., 2014). However, the process of natural restoration is slow, and engineering measures (e.g. artificial irrigation) that promote natural restoration are also required (Li et al., 2015). Although a series of projects with the aim of returning sloping arable land to forest have been implemented, many of these ecological restoration projects based on artificial tree-planting have failed, demonstrating the lack of practical support for this method. Afforestation may initially increase the vegetation cover, but it has a negative effect on biodiversity, and its ability to restore the eco-environment depends on both the type of re-vegetation carried out and the local environment (Lamb et al., 2005; Wang et al., 2014). Inappropriate restoration approaches might exacerbate soil moisture deficits and result in serious soil desiccation~~,~~ and a consequent reduction in vegetation cover (Wang et al., 2016; Wang et al., 2010b). Thus, the availability of water and other ecological conditions in the local region should be considered before undertaking vegetation restoration. Therefore, for more efficient ecological restoration of the Loess Plateau, it may be best to implement the more successful policies, such as prohibition of grazing and logging, and conversion of unsuitable cultivated sloping land to forest, while maintaining ~~the~~ natural species. In general, the distribution of economic crops, food crops, artificially planted vegetation, and natural vegetation should be sensitively and holistically arranged within the regional governance of the Loess Plateau, forming a complete landscape and complex ecosystem (Li et al., 2003; Feng et al., 2016). From the foregoing analysis, it can be inferred that both vegetation species and planting density should be considered based on local ecological conditions; this is of great significance for future vegetation restoration projects in areas of rapid water-induced soil erosion.

CONCLUSIONS

This study used a multiyear NDVI dataset from 1982 to 2013 and corresponding climate datasets to analyze spatio-temporal trends in NDVI on the Loess Plateau, China, and their relationship to climate change and human activity. The annual average NDVI exhibited an overall upward trend over the 32-year study period, especially in the central regions of the Loess Plateau. An investigation was conducted as to whether the NDVI response lagged behind monthly changes in precipitation and temperature. It was found that vegetation growth had the greatest correlation with precipitation when there was no lag (i.e. within the same month), whereas there was usually a one-month lag with temperature. Quantitative estimates were made of the relative effects of climate change and human activities on variations in NDVI after correcting for the time-lag effect. The results indicate that the contribution of human activities to variations in NDVI has become increasingly significant since the turn of the millennium, rising from 2.7% in the period from 1991–2000 to 30.4% from 2001–2013. This indicates that recent restoration measures are more effective than previous measures (which should be ~~cancelled~~ discontinued to avoid wasting human and financial resources). Increased vegetation coverage has reduced surface soil erosion on the Loess Plateau, leading in turn to a reduction in the volume of sediment delivered to the lower reaches of the Yellow River. We suggest that natural vegetation restoration is the most effective measure for control of erosion, and engineering measures that promote this should feature in the future governance of the Loess Plateau. A better match of vegetation species and planting density to the natural environment should be considered. Although other natural factors were found to have a limited effect on the results of the present study, it is recommended that, ~~provided~~ when suitable data become available, future assessments also consider the separate effects of ~~particular~~ other key natural factors like plant diseases, insect herbivory, and wildfire.

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Table 1. Results of the Mann-Kendall test for NDVI, precipitation, and temperature. Bold emphasis indicates that the trend was significant at the 95% confidence level.

Time	NDVI		Precipitation		Temperature	
	Z	Slope	Z	Slope / mm yr^{-1}	Z	Slope / ^{o}C yr^{-1}
January	-0.83	-0.0002	0.47	0.0244	0.24	0.0055
February	-0.86	-0.0002	1.54	0.0767	**2.51**	0.1040
March	-0.44	-0.0001	-1.70	-0.2591	**3.03**	0.0966
April	**2.55**	0.0007	-0.47	-0.0842	**2.40**	0.0609
May	**3.13**	0.0009	-0.08	-0.0687	1.86	0.0334
June	**2.32**	0.0010	-0.83	-0.3322	**4.10**	0.0624
July	**1.96**	0.0009	0.83	0.3447	**2.77**	0.0427
August	**2.68**	0.0011	-0.76	-0.3404	**2.77**	0.0400
September	**3.36**	0.0012	1.86	0.9025	1.12	0.0247
October	**4.01**	0.0019	-0.76	-0.1829	1.25	0.0236
November	1.05	0.0002	0.37	0.0365	1.51	0.0402
December	0.18	0.0000	0.00	-0.0003	0.34	0.0092
Annual	**3.91**	0.0007	0.37	0.4603	**3.36**	0.0440

Figure Captions:

Fig. 1 Location of the Loess Plateau and the distribution of meteorological stations.

Fig. 2 Schematic diagram illustrating quantitative assessment of the impact of climate change and human activities, and the impact of other natural factors on NDVI.

Fig. 3 Temporal variations in monthly and annual average NDVI for the Loess Plateau during the period 1982–2013.

Fig. 4 Spatial distribution of average NDVI for the Loess Plateau. (a) 1982–1990; (b) 1991–2000; (c) 2001–2007; (d) 2008–2013.

Fig. 5 Spatiotemporal changes in annual average NDVI throughout the Loess Plateau during the period 1982–2013.

Fig. 6 Comparison of average monthly precipitation (a), temperature (b), and NDVI (c) for the Loess Plateau over the period 1982–2013.

Fig. 7 Time lags between NDVI and precipitation (a) and temperature (b).

Fig. 8 Spatial distribution of soil erosion by water on the Loess Plateau from national surveys in 1995–1996 (a) and 2010–2012 (b). The difference in total soil removal between the two surveys (c).

Fig. 9 Annual sediment load at Tongguan and Huayuankou hydrological stations over the period 1982–2013.

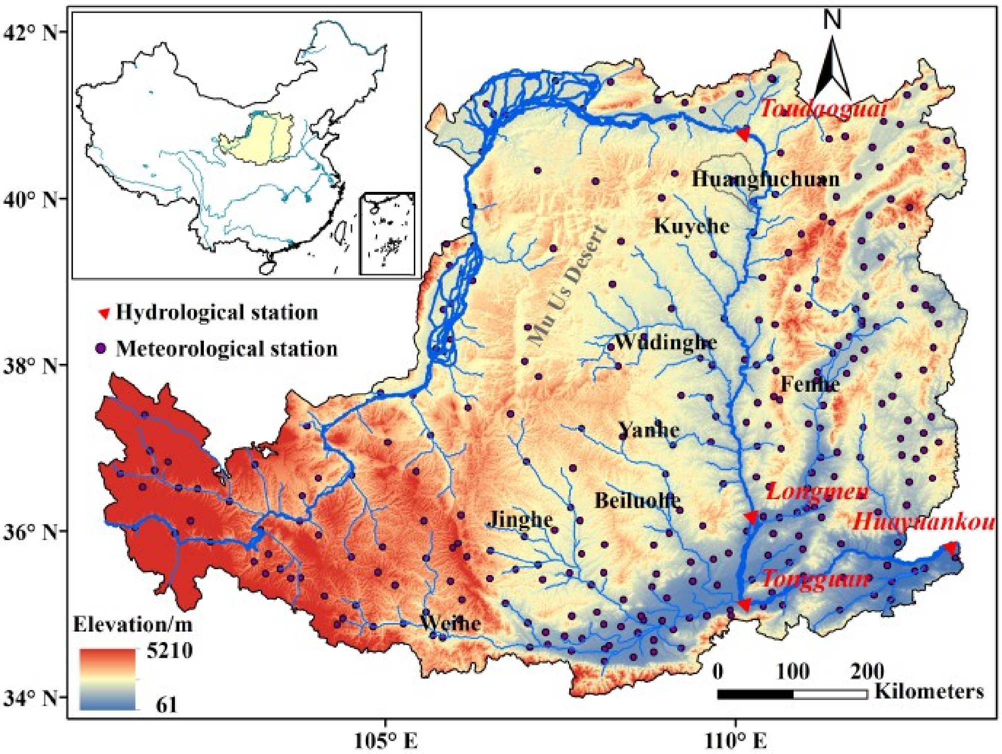

Fig. 1 Location of the Loess Plateau and the distribution of meteorological stations.

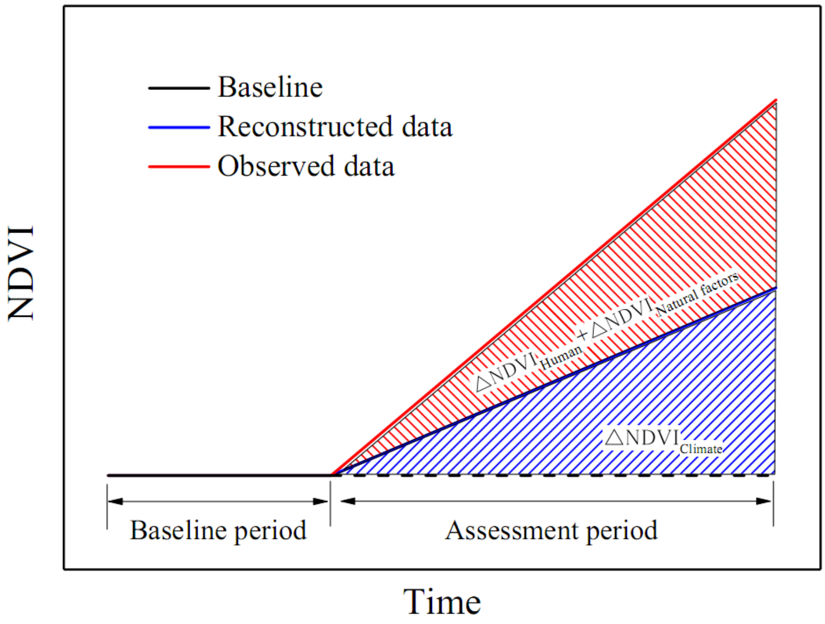

Fig. 2 Schematic diagram illustrating quantitative assessment of the impact of climate change and human activities, and the impact of other natural factors on NDVI.

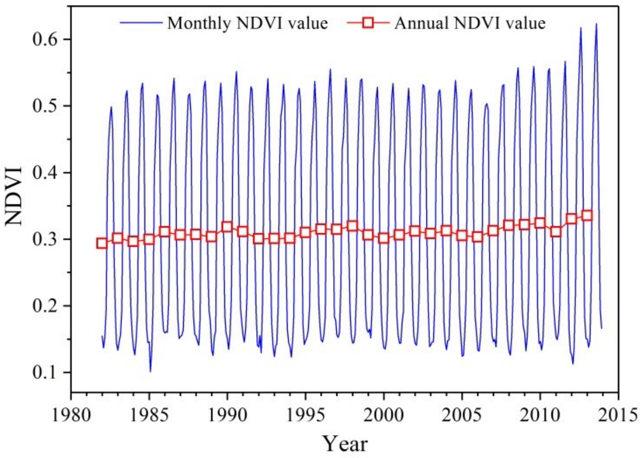

Fig. 3 Temporal variations in monthly and annual average NDVI for the Loess Plateau during the period 1982–2013.

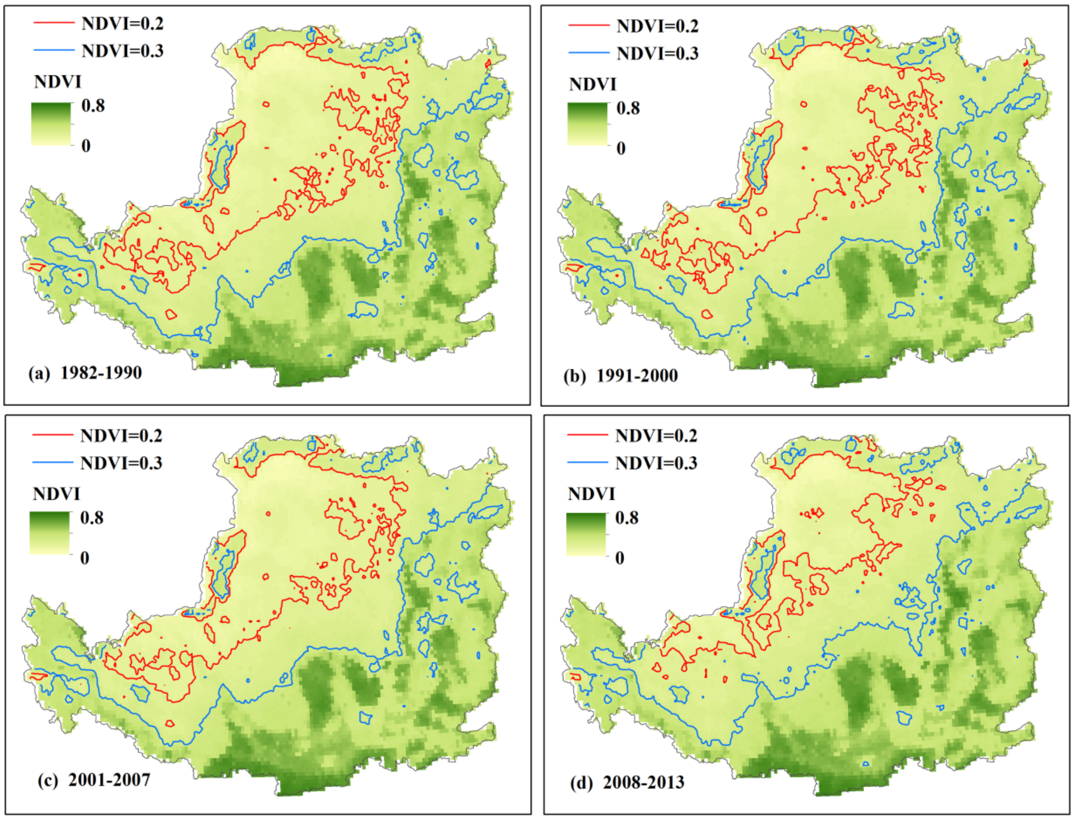

Fig. 4 Spatial distribution of average NDVI for the Loess Plateau. (a) 1982–1990; (b) 1991–2000; (c) 2001–2007; (d) 2008–2013.

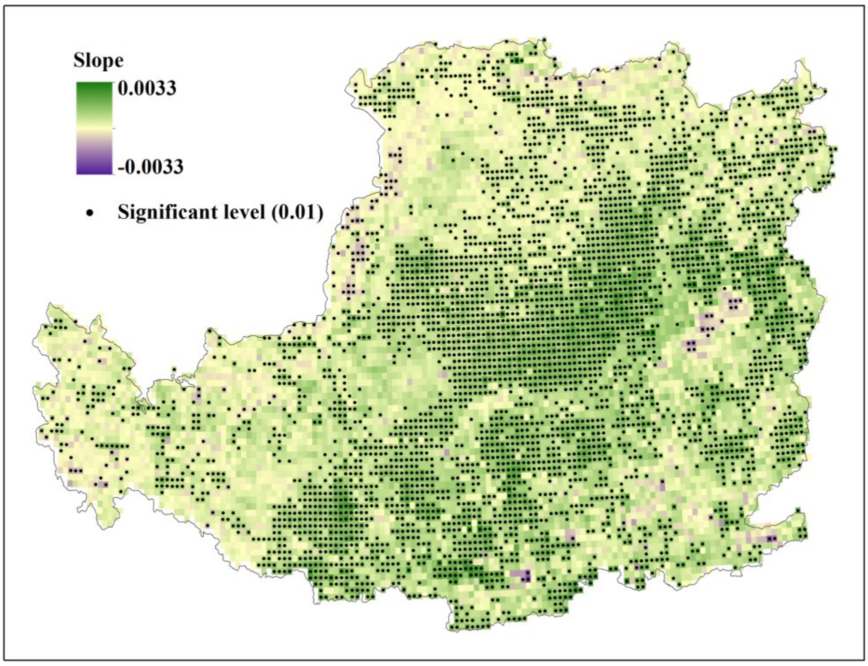

Fig. 5 Spatiotemporal changes in annual average NDVI throughout the Loess Plateau during the period 1982–2013.

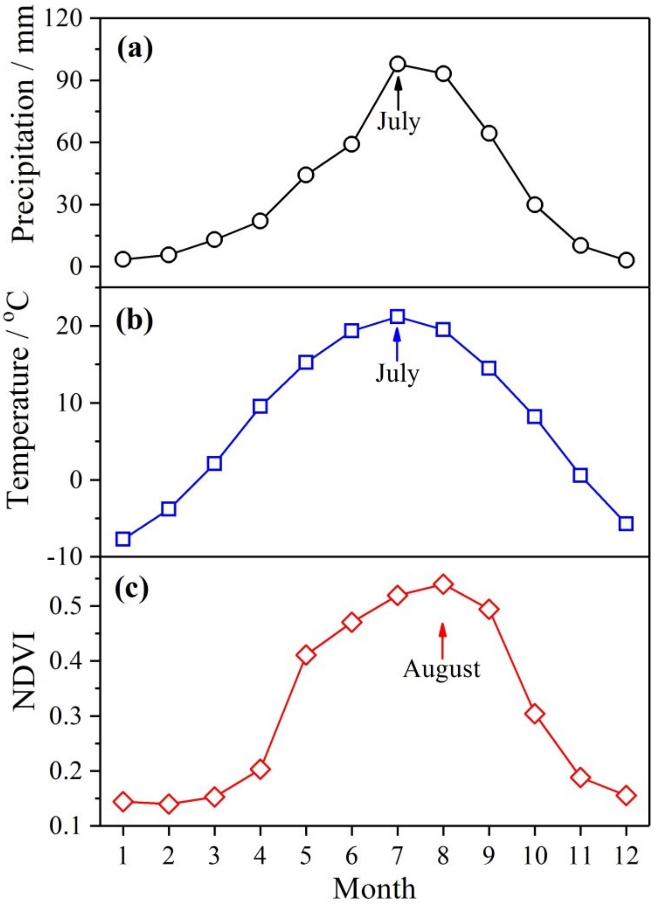

Fig. 6 Comparison of average monthly precipitation (a), temperature (b), and NDVI (c) for the Loess Plateau over the period 1982–2013.

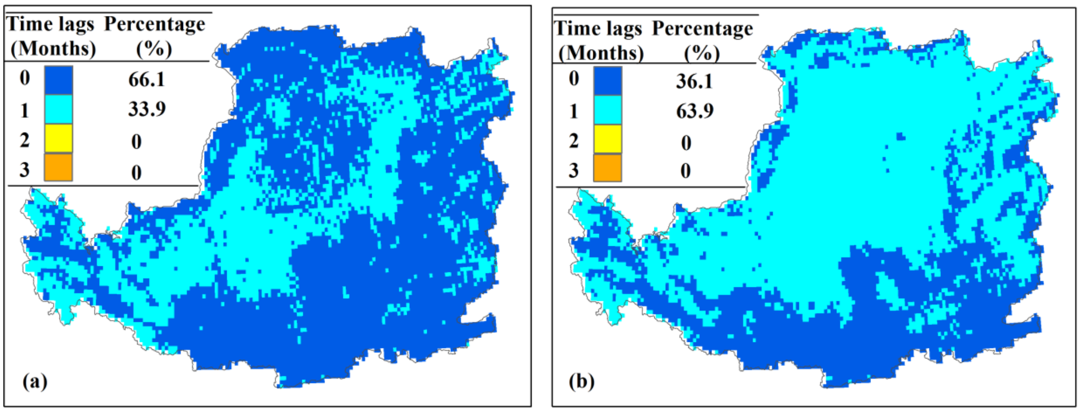

Fig. 7 Time lags between NDVI and precipitation (a) and temperature (b).

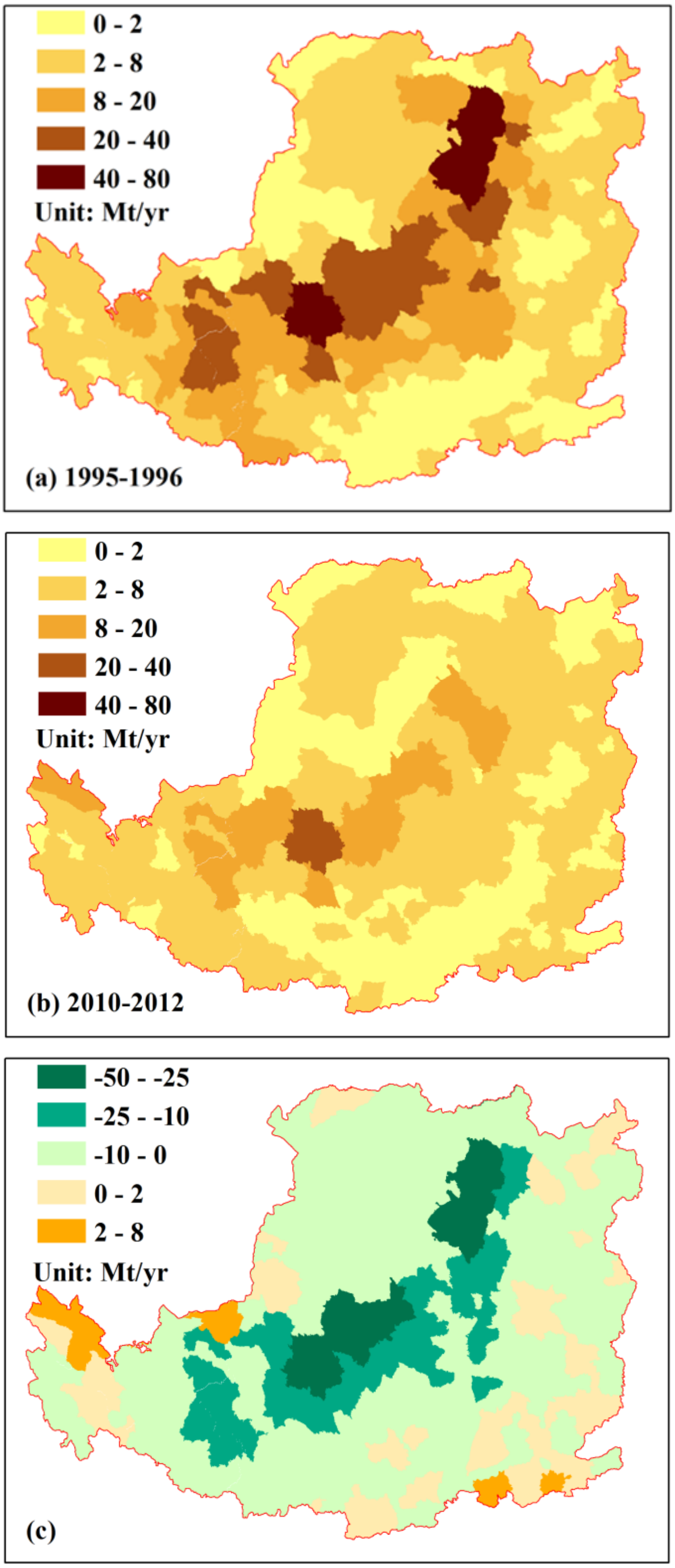

Fig. 8 Spatial distribution of soil erosion by water on the Loess Plateau from national surveys in 1995–1996 (a) and 2010–2012 (b). The difference in total soil removal between the two surveys (c).

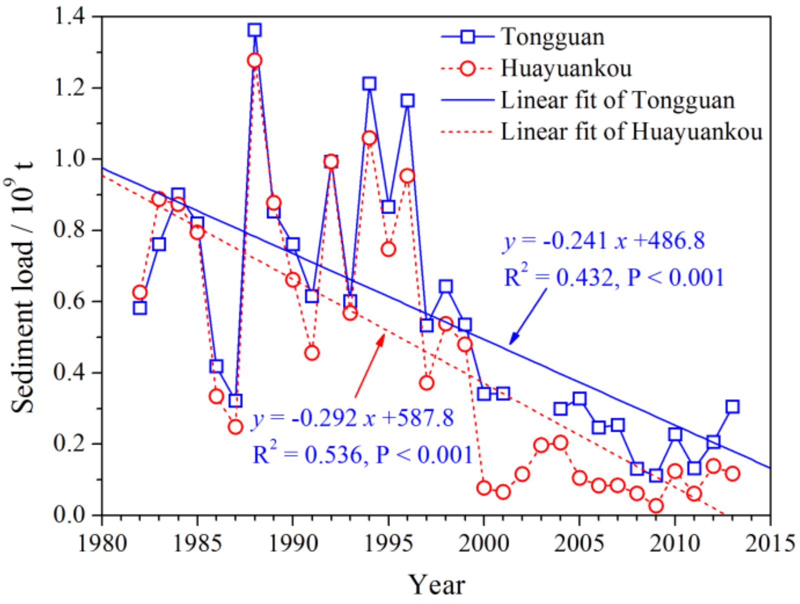

Fig. 9 Annual sediment load at Tongguan and Huayuankou hydrological stations over the period 1982–2013.

SUPPORTING INFORMATION

Table S1. Contribution of climate change and human activities to variations in NDVI.

Time periods	Observed average NDVI	Reconstructed average NDVI	$\Delta NDVI_{total}$	$\Delta NDVI_{climate}$	$\Delta NDVI_{human}$
1991-2000	0.3082	0.3081	0.0039	0.0038 (97.3%)	0.0001 (2.7%)
2001-2013	0.3157	0.3123	0.0115	0.0080 (69.6%)	0.0035 (30.4%)
1991-2013	0.3125	0.3104	0.0082	0.0062 (75.4%)	0.0020 (24.6%)

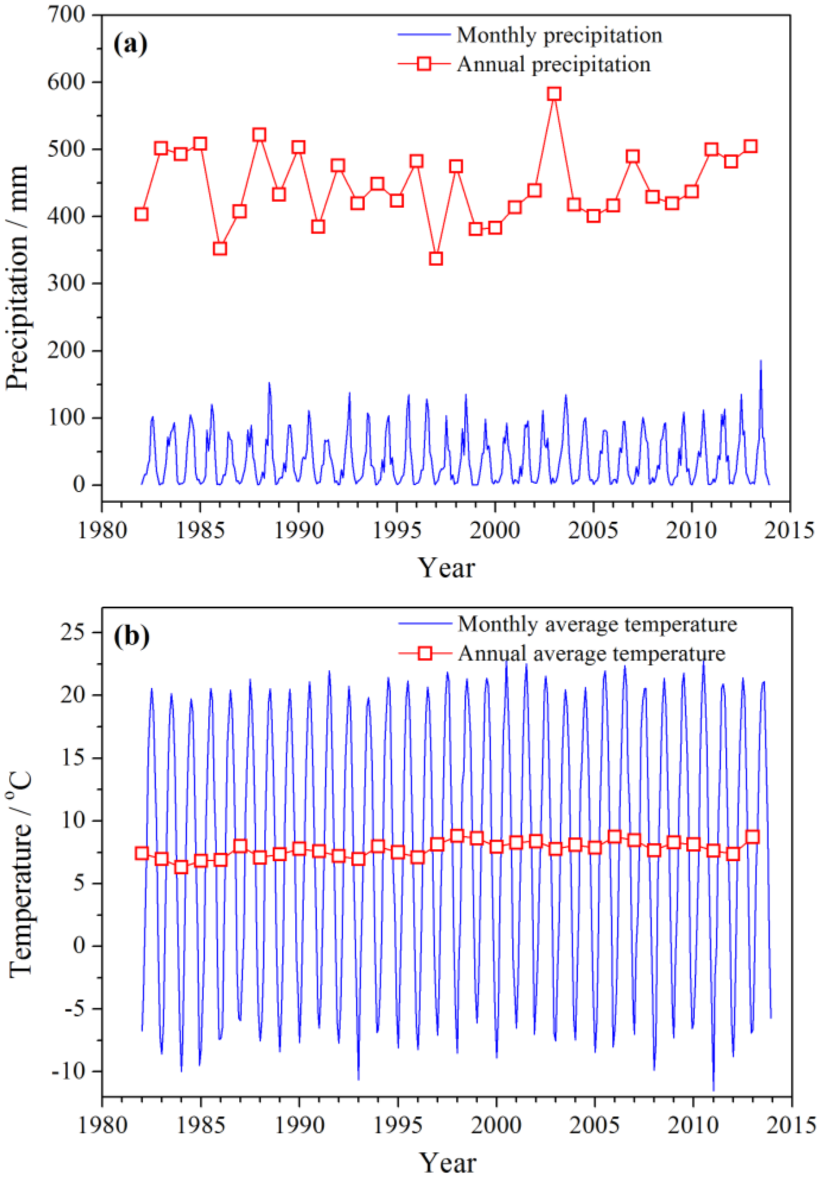

Fig. S1 Temporal variations in annual precipitation (a) and average temperature (b) for the Loess Plateau during the period 1982–2013.

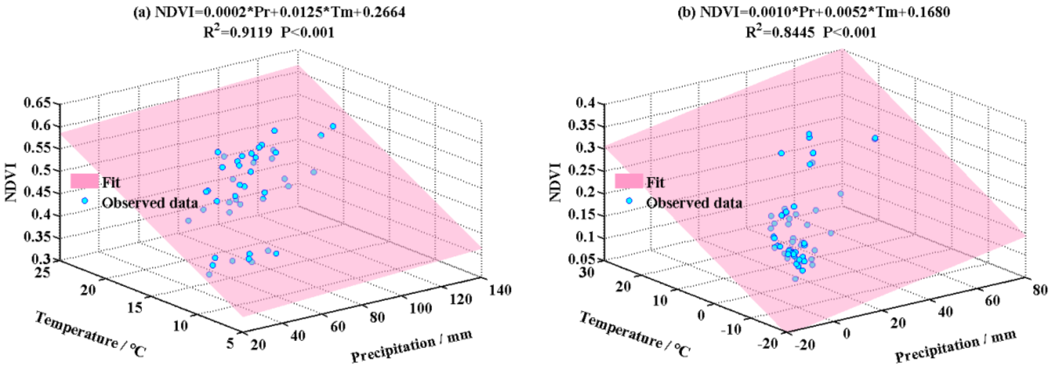

Fig. S2 Relationship between NDVI and climate factors in the growing season (a) and the non-growing season (b) during the baseline period of 1982–1990. The relationships were obtained by multiple linear regression analysis.

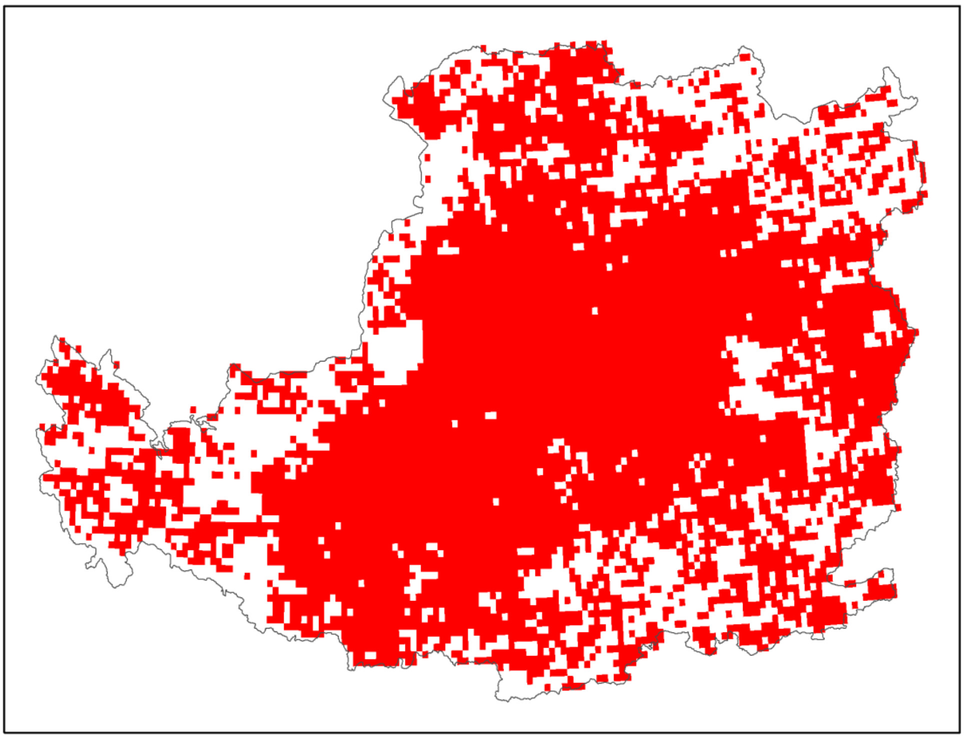

Fig. S3 Consistency test for changes in NDVI and soil erosion on the Loess Plateau during the period 1995–2012. Cases where soil erosion was reduced (worsened) while the NDVI increased (decreased) were considered consistent, and the red pixels represent the region which passed the consistency test.