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Soil erosion and its response to the changes of precipitation and vegetation cover on the Loess Plateau

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Abstract: Soil erosion is a major threat to our terrestrial ecosystems and an important global environmental problem. The Loess Plateau in China is one of the regions that suffered more severe soil erosion and undergoing climate warming and drying in the past decades. The vegetation restoration named Grain-to-Green Program has now been operating for more than 10 years. It is necessary to assess the variation of soil erosion and the response of precipitation and vegetation restoration to soil erosion on the Loess Plateau. In the study, the Revised Universal Soil Loss Equation (RUSLE) was applied to evaluate annual soil loss caused by water erosion. The results showed as follows. The soil erosion on the Loess Plateau between 2000 and 2010 averaged for 15.2 t hm^{-2} a^{-1} and was characterized as light for the value less than 25 t hm^{-2} a^{-1}. The severe soil erosion higher than 25 t hm^{-2} a^{-1} was mainly distributed in the gully and hilly regions in the central, southwestern, and some scattered areas of earth-rocky mountainous areas on the Loess Plateau. The soil erosion on the Loess Plateau showed a deceasing trend in recent decade and reduced more at rates more than 1 t hm^{-2} a^{-1} in the areas suffering severe soil loss. Benefited from the improved vegetation cover and ecological construction, the soil erosion on the Loess Plateau was significantly declined, especially in the east of Yulin, most parts of Yan'an prefectures in Shaanxi Province, and the west of Luliang and Linfen prefectures in Shanxi Province in the hilly and gully regions. The variation of vegetation cover responding to soil erosion in these areas showed the relatively higher contribution than the precipitation. However, most areas in Qingyang and Dingxi prefectures in Gansu Province and Guyuan in Ningxia Hui Autonomous Region were predominantly related to precipitation.

Keywords: soil erosion; assessment; precipitation; vegetation cover; Loess Plateau

1 Introduction

Soil erosion is widespread and a major environmental threat to our terrestrial ecosystems

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(Belyaev *et al*., 2005; Singer and Warkentin, 1996). The Chinese Loess Plateau is one of the most severely eroded regions in the world (Liu and Liu, 2010; Ritsema, 2003; Zheng *et al*., 2005). Severe soil erosion had not only led to the impoverishment of cultivated land causing poverty of local people, but also to desertification that destroys land conditions crucial for human survival.

The change of soil erosion was related to precipitation, soil properties, topography and land cover change. Among these factors, soil and topography, generally speaking, are relatively stable and change little. Therefore, the variation of soil erosion was mainly driven by the changes of precipitation and vegetation cover, which could retard or accelerate the process of soil erosion (Alatorre *et al*., 2012; Mohammad and Adam, 2010; Sharma *et al*., 2011; Zhu and Zhu, 2012). The precipitation is important for determining the severity of soil and water loss. Rainfall with low intensity mostly cannot produce severe soil erosion, even if experiencing high frequencies (Asselman *et al*., 2003). The variation of precipitation will also influence soil water content, which then influences the dynamics of vegetation development and succession under different land uses, and thus eventually decreases or accelerates erosion (Hou *et al*., 1996). Vegetation restoration can also improve the effectiveness of land cover and reduce susceptibility to soil erosion (Ritsema, 2003). The relationships between precipitation, vegetation and erosion become uncertain and complex due to their interactions. To some extent, positive or negative correlation between precipitation and erosion mainly depends on the condition of vegetation cover (Wei *et al*., 2010; Xu, 2005). Several studies under different environmental conditions have demonstrated the positive effect of vegetation cover in reducing the water erosion (Mohammad and Adam, 2010; Nunes *et al*., 2011), and its negative effect for loss of vegetative cover as a result of human activities leading to increment of the risk of runoff and soil erosion (Asselman *et al*., 2003; Vásquez-Méndez *et al*., 2010).

In the last 50 years, the climate of Loess Plateau had an obvious tendency of warming and drying (Liu *et al*., 2006; Xin *et al*., 2008; Yao *et al*., 2005). There is a common sense that decreased rainfall would reduce the region's rainfall erosivity and eventually lower the soil loss. However, it may also theoretically lower the density of vegetation cover for lacking of enough water in the arid and semi-arid areas, causing the erosion increment. Since 1998, the Chinese government had launched the Grain-to-Green Program, which has been mainly directed to soil and water conservation on the Loess Plateau. Many infrastructure reforms and ecological projects were undertaken including construction of large reservoirs and silt dams, afforestation, and converting cropland on steep slopes to forest and grassland (Chen *et al*., 2010; Gao *et al*., 2010; Xin *et al*., 2008). Positive effects have been achieved through the recovery of the natural vegetation (Fu *et al*., 2011).

Some studies have revealed that the runoff and sediment from the Loess Plateau to the Yellow River had decreased significantly in recent decades, which was closely related to the soil erosion condition on the Loess Plateau (Kang *et al*., 2001; Wang *et al*., 2007). On the one hand, the decreased trend of runoff and sediment was attributed to the climate changes as the annual precipitation decreased slightly while the annual temperature and evaporation increased significantly (Wang *et al*., 2007; Zhang *et al*., 2008). On the other hand, more attention was paid to the vegetation restoration on the Loess Plateau since the implementation of the Grain-to-Green Program (Fu *et al*., 2011). Only a limited amount of research has been undertaken on the effects of climate change on soil erosion and how this might relate to human modification of vegetation cover initiated by policies such as the Grain-to-Green Program. The program has now been operating for more than 10 years under the warming and drying climate. However, little knowledge about ecological effect of vegetation recovery on the soil erosion has been reported.

Therefore, in this study, we quantitatively assessed the impacts of vegetation cover and precipitation change on the soil erosion on the Loess Plateau. This assessment is required for scientific support for ongoing implementation and evaluation of ecological construction and environmental management programs.

2 Study area and methods

2.1 Description of study area

The Loess Plateau region (Figure 1), located in the upper and middle reaches of the Yellow River Basin, northwestern China, lies between longitudes 100°54′–114°33′E and latitudes 33°43′–41°16′N, covering an area of more than 620,000 km^2, 6.5% of the area of China. It extends to Yinshan Mountains in the north, Qinling Mountains in the south, Wuqiaoling-Riyue Mountains in the west and Taihang Mountains in the east. It has very complex topography, including sub-plateaus, basins, hills and gullies, with elevation ranging from 100 to 5000 m. Most of the Plateau has sub-humid and semi-arid climates with an average annual temperature of 4.3℃ in the northwest and 14.3℃ in the southeast (Li *et al*., 2012). Average annual precipitation ranges from 150 mm in the northwest to 750 mm in the southeast and mostly falls as high intensity rainstorms between June and September (Li *et al*.,

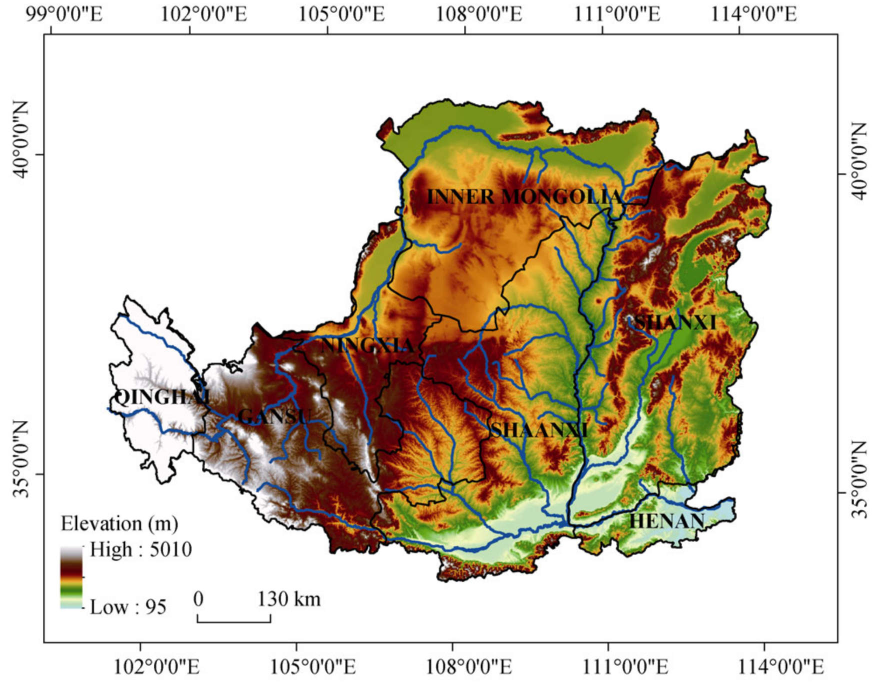

Figure 1 Location of the Loess Plateau, China

2009). The Plateau surface is covered by highly erodible loess layers averaging 100 m deep and soil types in most parts are typical loess and clayey loess (Liu, 1964). Natural vegetation types vary from arid desert, to steppe and then to broad-leaved deciduous forest in the direction from northwest to southeast (Yang and Yuan, 1991). The major crops are wheat, corn, millet, sorghum, soybean, and buckwheat.

The natural vegetation on the Loess Plateau has been largely destroyed by deforestation and cultivation. The combined effects of frequent heavy rainfalls during summer, steep topography, low vegetation cover and highly erodible loess soil have made the Loess Plateau the most severely eroded areas in the world. A large amount of the eroded soil was transported into the Yellow River, carrying an annual sediment load of 16.4×10^9 t (Zhang and Liu, 2005). The 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. The Chinese government has made great efforts to control soil erosion, an ecological restoration program, designated “Grain to Green” was initiated on the Loess Plateau.

2.2 Method

2.2.1 Revised Universal Soil Loss Equation

The Revised Universal Soil Loss Equation (RUSLE) represents how climate, soil, topographic slope and slope length as well as vegetation cover affect soil erosion caused by rainfall impact and surface runoff (Renard *et al*., 1997). It has been extensively used to estimate soil erosion loss and to assess erosion risk. It is the statistical relationship model established and can be developed better according to the local conditions of these factors. It can be used on the Loess Plateau where water erosion is the dominant cause of soil loss (Fu *et al*., 2011). The RUSLE equation is:

$$A = R \times K \times L \times S \times C \times P \tag{1}$$

where A is the amount of the average soil loss (t hm^{-2} a^{-1}); R the rainfall erosivity factor (MJ mm hm^{-2} h^{-1} a^{-1}); K the soil erodibility factor (t hm^2 h hm^{-2} MJ^{-1} mm^{-1}); L the slope length factor; S the slope factor; C the vegetation cover factor and P the erosion control practice factor. Factors C and P are dimensionless.

Rainfall erosivity factor (R)

The rainfall erosivity index (R) in RUSLE model is an index of rainfall erosivity which is the potential ability of the rain to cause erosion. It is the driving force of erosion, and has direct relationships with soil erosion (Angulo-Martinez and Begueria, 2009; Renard *et al*., 1997). In this study, the annual rainfall erosivity was calculated using the method of Zhang *et al*. (2002), a method based on aggradations of half-month rainfall erosivity using daily rainfall data that has been widely used in China (Cheng *et al*., 2009; Men *et al*., 2008; Zhang, 2003). The annual rainfall erosivity was estimated as follows:

$$M_i = \alpha \sum_{j=1}^{k} (D_j)^{\beta} \tag{2}$$

where M_i is the half-month rainfall erosivity (MJ mm hm^{-2} h^{-1} a^{-1}) and D_j is the effective rainfall for day j in one half-month. D_j is equal to the actual rainfall if the actual rainfall is larger than the threshold value of 12 mm, which is the standard for China’s erosive rainfall. Otherwise, D_j is equal to zero (Xie *et al*., 2000). The term k is the number of days in the half-month. The terms α and β are the undetermined parameters:

$$\beta = 0.8363 + \frac{18.177}{\overline{P}_{d12}} + \frac{24.455}{\overline{P}_{y12}} \tag{3}$$

$$\alpha = 21.586\beta^{-7.1891} \tag{4}$$

where $\overline{P}_{d12}$ is the average daily rainfall that is more than 12 mm and $\overline{P}_{y12}$ is the yearly average rainfall for days with rainfall more than 12 mm.

Soil erodibility factor (K)

The soil erodibility represents both susceptibility of soil to erosion and the amount and rate of runoff, as measured under standard plot conditions (Parysow *et al.*, 2003). The K-factor is related to soil texture, organic matter content permeability, and other factors and is basically derived from the soil type (Wischmeier *et al.*, 1971). In this study the soil erodibility factor was determined using the EPIC equation (Williams *et al.*, 1984) as follows:

$$K = \left\{0.2 + 0.3\exp\left[-0.0256\mathrm{SAN}\frac{(1-SIL)}{100}\right]\right\}\left(\frac{SIL}{CLA+SIL}\right)^{0.3} \times$$
$$\left(1.0 - \frac{0.25C}{C+\exp(3.72-2.95C)}\right)\left(1.0 - \frac{0.7SNI}{SNI+\exp(-5.51+22.9SNI)}\right)\times 0.1317 \tag{5}$$

where SAN, SIL and CLA are the sand fraction (%), silt fraction (%), and clay fraction (%), respectively, C is the soil organic carbon content (%), and SNI is equal to 1-SAN/100. 0.1317 is the conversion factor from US customary units to SI units.

Topographic factor (LS)

The LS factor reflects the effect of slope length and the slope gradient on erosion (Lu *et al.*, 2004). A DEM-based procedure developed in USA (Hickey, 2000; Van Remortel *et al.*, 2001) was employed to resolve the difficulties for the estimation of the LS-factor on a regional scale. However, the LS factor algorithms was limited to slopes ⩽18% because data used to develop RUSLE involved slopes up to 18% only (McCool *et al.*, 1989). Liu *et al.* (1994) fixed the formula using soil loss data from natural runoff plots ranging from 9% to 55% slopes and reported that soil loss was linearly related to the sine of the slope angle. Therefore, in this study the formula for L defined and developed by McCool *et al.* (1987, 1997) and incorporation of the equations for slope gradient >18% formulated by Liu *et al.* (1994) was used:

$$L = \left(\frac{\gamma}{22.13}\right)^m \quad \begin{cases} m = 0.5 & \theta \geqslant 9 \\ m = 0.4 & 9 > \theta \geqslant 3 \\ m = 0.3 & 3 > \theta \geqslant 1 \\ m = 0.2 & 1 \geqslant \theta \end{cases} \tag{6}$$

$$S = \begin{cases} 10.8\sin\theta + 0.03, & \theta < 9\% \\ 16.8\sin\theta - 0.05, & 9\% \leqslant \theta \leqslant 18\% \\ 21.91\sin\theta - 0.96, & \theta > 18\% \end{cases} \tag{7}$$

where γ is the slope length (m); m is a dimensionless constant depending on the percent slope (θ).

Vegetation cover factor (C)

Vegetation is the most sensitive factor influencing soil erosion and soil loss is significantly related to vegetation coverage (Renard *et al*., 1997) in a negative exponential relationship, whose turning point is about 78.3% (Wang and Liu, 1999). Cai *et al*. (2000) developed a method for C factor estimation using vegetation cover based on simulated and natural rainfall on experimental plots. The formula is expressed as:

$$C=\begin{cases} 1 & f=0 \\ 0.6508-0.3436\lg f & 0<f\leqslant 78.3\% \\ 0 & f>78.3\% \end{cases} \tag{8}$$

Vegetation coverage (f) was calculated using NDVI, which can better characterize vegetation cover.

$$f=\frac{(NDVI-NDVI_{soil})}{(NDVI_{max}-NDVI_{soil})} \tag{9}$$

where $NDVI_{soil}$ is NDVI value for pure bare soil pixel; $NDVI_{max}$ refers to NDVI value for regional pure vegetation pixel.

Erosion control practice factor (P)

The erosion control practice factor was considered the most difficult factor to determine and was the least reliable factor of the RUSLE input factors (Renard *et al*., 1997). For this study, the erosion control practice factor (P) was roughly determined from the land use classification map on the Loess Plateau (Liu *et al*., 2005) (Table 1).

Table 1 Values of the erosion control practice factor (P) based on the land use map of the Loess Plateau, China

Land use	Woodland	Grassland	Cropland				Others
			Flat	Hills	Mountains	Steep slope(>25)	
P value	1	1	0.20	0.35	0.65	0.80	1

2.2.2 Trend analysis

The annual variation trends for soil erosion, vegetation cover and precipitation during the years from 2000 to 2010 were calculated by the slope equation described below. The slope equation was estimated by fitting linear functions using ordinary least-squares regression. It indicated the strong or weak, positive or negative trends for the variables. The boundaries were defined from a 95% confidence interval for the slope. The slope is expressed as:

$$Slope=\frac{n\times\sum_{i=1}^{n} i\times var_i-\sum_{i=1}^{n} i\sum_{i=1}^{n} var_i}{n\times\sum_{i=1}^{n} i^2-\left[\sum_{i=1}^{n} i\right]^2} \tag{10}$$

where i is the number of years; n is the total number of years; var is the variable of time-series trend.

2.2.3 Multiple linear regression analysis

Multiple linear regressions were applied for examining the relationship of a collection of independent variables (or predictors) for precipitation and vegetation cover to a single dependent variable (or criterion) for soil erosion between 2000 and 2010 on the Loess Plateau. The dependent variable for soil erosion and both of independent variables for precipitation and vegetation cover in 2000–2010 were normalized between 0 and 1 using the min-max normalization algorithm before entering into the regression model. A robust regression using iteratively reweighted least-squares model (Holland and Welsch, 1977) based on the pixel scales was applied to detect the significances and contribution rates of precipitation and vegetation cover corresponding to the changes of soil erosion. The procedures were performed using the robust-fit function of matlab 7.10.0 software.

2.3 Datasets

Daily rainfall data provided by the National Meteorological Information Centre of China (http://cdc.cma.gov.cn/) from 133 meteorological stations, 72 were on the Loess Plateau and the remaining 61 were located adjacent to the Plateau, were used to analyze the annual rainfall erosivity on the Loess Plateau. Soil organic carbon and texture data were collected and calculated for soil erodibility factor, which were derived from the Second Soil Investigation in China (Wei *et al*., 2012). DEM Dataset with a resolution of 90 m developed from SRTM (Shuttle Radar Topography Mission) was computed to topographic factor in the study, which was available from the International Scientific and Technical Data Mirror Site, Computer Network Information Center, CAS. (http://datamirror.csdb.cn). The monthly 1 km NDVI (Normalized Differential Vegetation Index) MOD13A products between 2000 and 2010 were performed for vegetation cover factor and obtained from NASA EOS DATA Gateway (https://wist.echo.nasa.gov/api).

3 Results and discussion

3.1 Spatial and temporal characteristics of soil erosion on the Loess Plateau

Water erosion is the dominant soil loss mode on the Loess Plateau (Tang, 2004). According to the Standard for Classification and Gradation of Soil Erosion SL190-2007 (Ministry of Water Resources of PR China, 2008), water erosion could be classified into six levels, i.e., slight (less than 10 t hm^{-2} a^{-1}), light (10–25 t hm^{-2} a^{-1}), moderate (25–50 t hm^{-2} a^{-1}), severe (50–80 t hm^{-2} a^{-1}), very severe (80–150 t hm^{-2} a^{-1}) and extremely severe (more than 150 t hm^{-2} a^{-1}). In this study, soil erosion on the Loess Plateau with an average of 15.2 t hm^{-2} a^{-1} was identified as light soil erosion, being less than 25 t hm^{-2} a^{-1} between 2000 and 2010 (Figure 2). The soil erosion less than 25 t hm^{-2} a^{-1} accounted for 80.5% of the total area and was mainly distributed in irrigated regions, plain areas, sandy areas and earth-rocky mountainous areas. The more severe soil erosion higher than 25 t hm^{-2} a^{-1} was mainly distributed in gully and hilly regions in the central and southwestern parts, where the fragmented topography, well-developed gullies and steep slopes, and some scattered areas of earth-rocky mountainous areas were common characteristics of the Loess Plateau.

The annual change of soil erosion from 2000 to 2010 was shown in Figure 3. Soil loss for most parts of the Loess Plateau declined at a rate of about 1 t hm^{-2} a^{-1}. Erosion reduced at rates between 1 and 3 t hm^{-2} a^{-1} was observed in the areas suffering more severe soil loss on the Loess Plateau. These areas included the east of Yulin, most of the area of Yan'an prefecture (the northern part of Shaanxi Province), the west of Luliang and Linfen prefectures (the central part of Shanxi Province), Zhongwei and Guyuan prefectures (the southern part of Ningxia), east of Lanzhou and most of Qingyang (Gansu Province), which were mostly gully and hilly regions in central and southwestern parts along the Yellow River and its

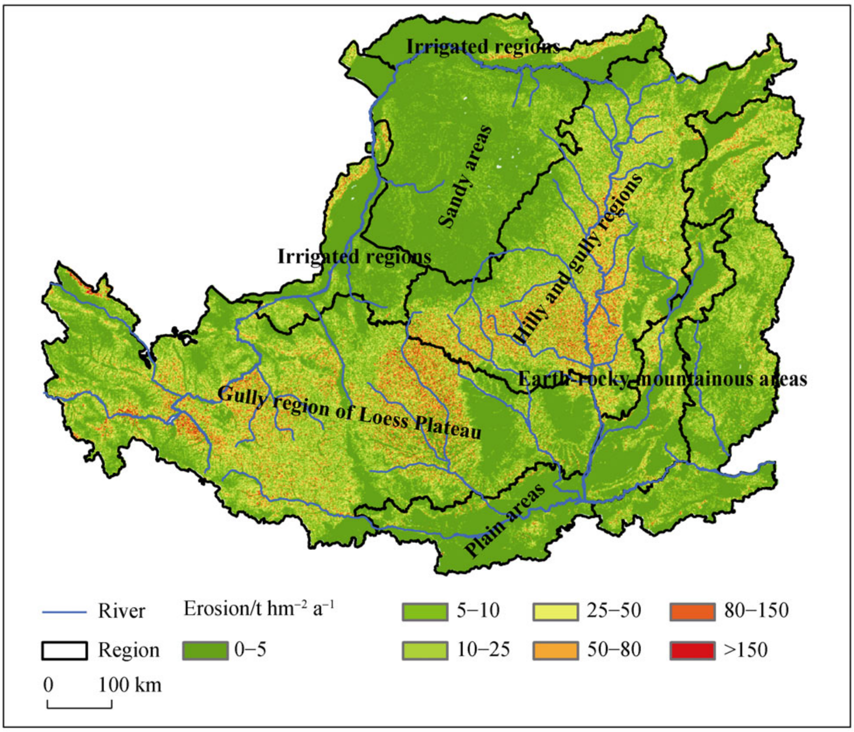

Figure 2 The spatial distribution of soil erosion averaged between 2000 and 2010 on the Loess Plateau, China

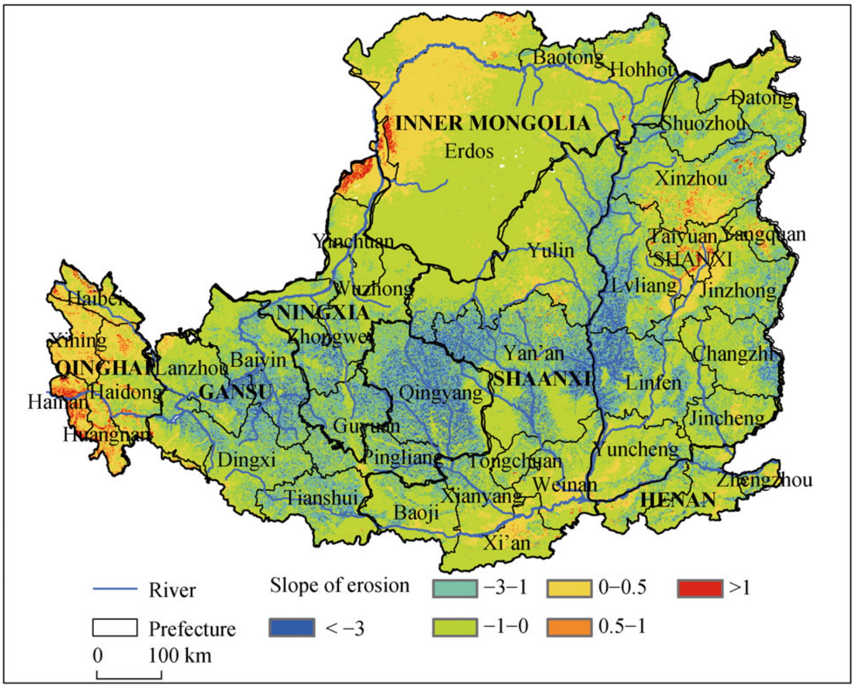

Figure 3 The spatial distribution of annual changes of soil erosion between 2000 and 2010 on the Loess Plateau, China.

tributaries, and in some earth-rocky mountainous areas. Soil erosion decreased significantly at rates higher than 3 t hm^{-2} a^{-1} occurred in Yan'an, Qingyang, Luliang and Linfen prefectures, which were the key areas of soil and water conservation and ecological restoration. These results were very similar to that reported in other studies, the areas suffered heavy soil and water loss had now shrunk, and the soil erosion rate in these region had declined from 33.5 to 23.9 t hm^{-2} a^{-1} between 2000 and 2008, particularly on the sloping land where soil erosion mainly occurs (Wei *et al*., 2010; Fu *et al*., 2011). An indirect example was shown that the suspended sediment flux decreased 16% from the Yellow River (Dai *et al*., 2009). However, in our study the soil erosion increased at the rate up to 1 t hm^{-2} a^{-1} over the ten years in some areas, which were in the western part of Erdos (Inner Mongolia Autonomous Region), the surroundings of Taiyuan city (Shanxi Province), and the eastern parts of Xining, Hainan and Huangnan prefectures (the east of Qinghai Province).

3.2 Response of soil loss to the changes of precipitation and vegetation cover

Precipitation and vegetation cover are two direct and sensitive factors that affected the soil erosion (Hudson, 1995; Quan *et al*., 2011; Renard *et al*., 1997). The precipitation is a destructive force to the land surface making the soil prone to splash erosion, and is important for determining the severity of soil and water loss. Vegetation cover has the positive effects on the land surface for protecting soil surface from erosion. The increment of vegetation can improve the effectiveness of land cover and reduce susceptibility to soil erosion (Ritsema, 2003). In the last 60 years, the climate of the Loess Plateau had an obvious trend of warming and drying (Liu *et al*., 2006; Xin *et al*., 2011). At the same time, lots of infrastructure and ecological reconstructions were carried out on the Loess Plateau, especially returning farmland to forest and grassland (Fu *et al*., 2009; Gao *et al*., 2010). The soil erosion would be significantly changed due to the variation of precipitation and vegetation cover, especially in the zone of fragile ecosystem and semiarid climate on the Loess Plateau.

On the Loess Plateau, erosion rate change predominantly related to precipitation, rather than by erosion-resistance of vegetation, was shown in Qingyang Prefecture in Gansu and Guyuan Prefecture in Ningxia. In these prefectures soil erosion declined markedly as precipitation decreased (Figure 4), but there was little increment of vegetation cover (Figure 5).

However, evident erosion-resistance due to vegetation cover (Figure 5) was shown for regions along the Yellow River and its tributaries, particularly at slopes greater than 25°. These areas were located in the east of Yulin, most parts of Yan'an prefecture in Shaanxi, and the west of Luliang and Linfen prefectures in Shanxi in hilly and gully regions on the Loess Plateau. They were the key areas for soil and water conservation and ecological restoration undertaken by the National Grain-to-Green Program and a large area of steep slope cropland has been converted into grasslands and forests (Xin *et al*., 2008). The decrease of soil erosion in these areas was mainly driven by significant increments of vegetation cover, whereas precipitation increased relatively more in Yulin and Luliang prefectures and little change in Yan'an and Linfen prefectures (Figure 4).

3.3 The significant tests of precipitation and vegetation cover responding to soil erosion

Statistical P values were calculated to analyze the significant tests for soil erosion based on the variation of precipitation (Figure 6) and vegetation cover (Figure 7). The P values

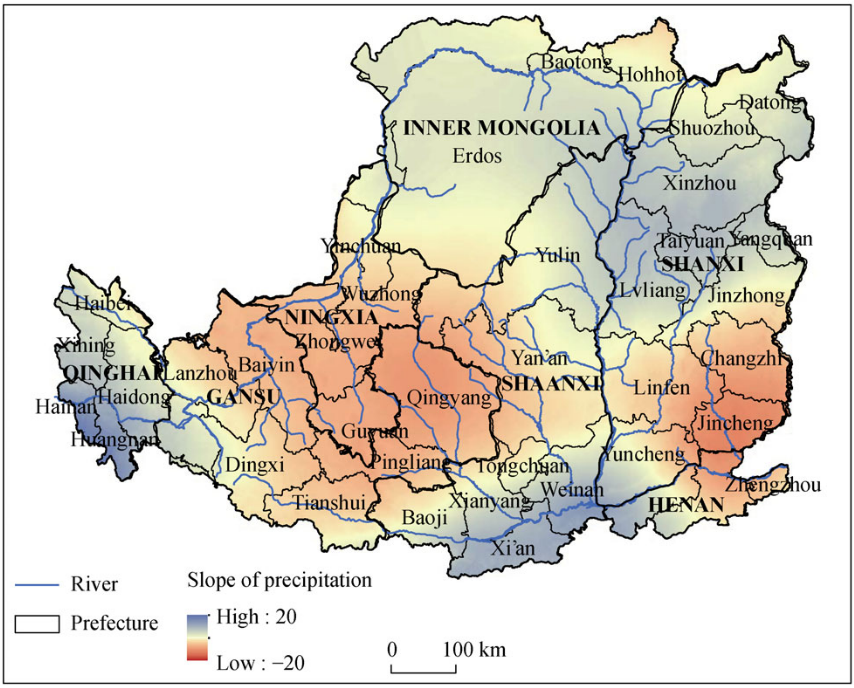

Figure 4 The variation of precipitation between 2000 and 2010 on the Loess Plateau, China

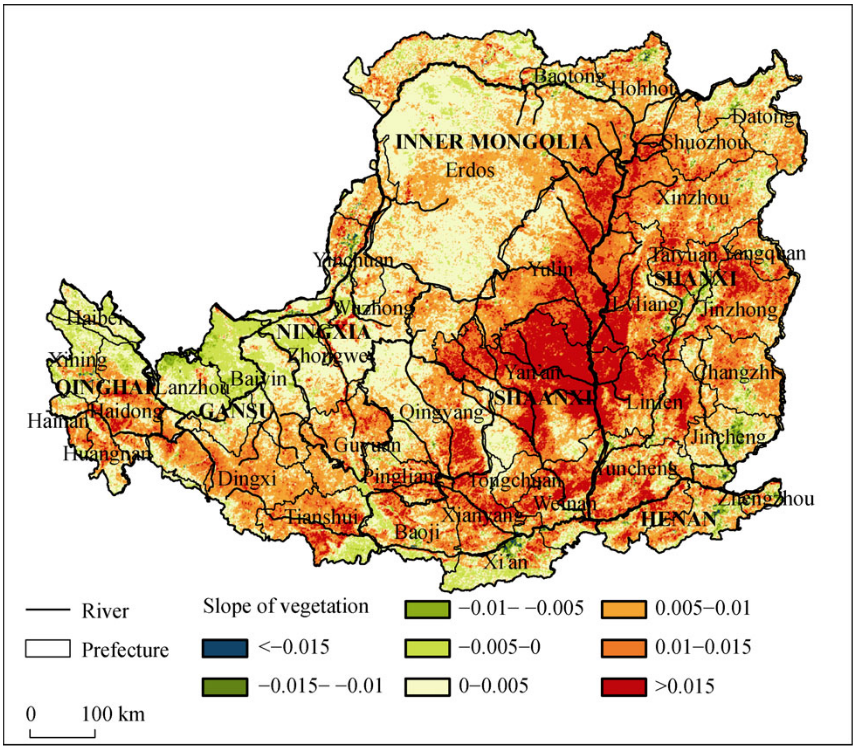

Figure 5 The variation of vegetation coverage between 2000 and 2010 on the Loess Plateau, China (the value of vegetation coverage ranging from 0 to 1)

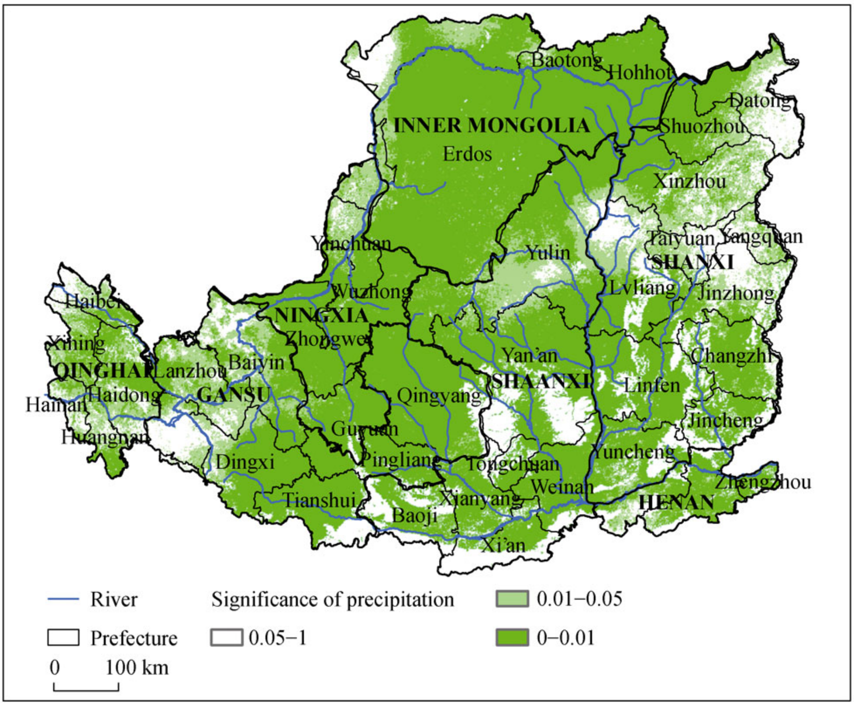

Figure 6 The significance analysis of precipitation on soil erosion in 2000-2010

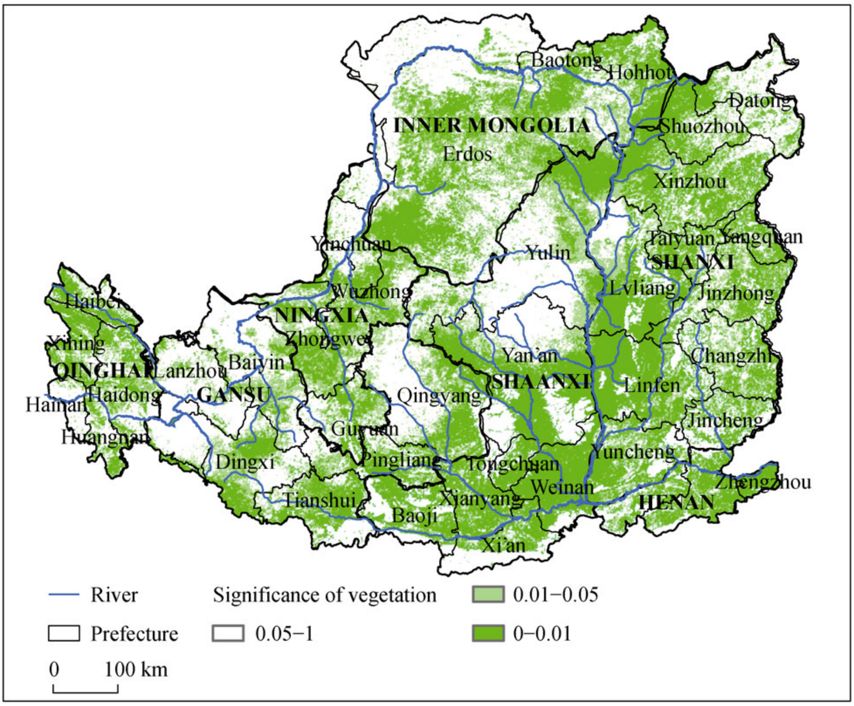

Figure 7 The significance analysis of vegetation on soil erosion in 2000-2010

map was divided into three categories, significance at 0.05 and 0.01 levels and no significance (P>0.05). The significant areas (with P values less than 0.05) of precipitation corresponding to soil erosion mostly located in gully and hilly regions, irrigated regions and sandy areas. These areas included Yulin and Yan'an prefectures in Shaanxi, and Luliang and Linfen prefectures in Shanxi in the hilly and gully region, Zhongwei and Guyuan prefectures in Ningxia, Qingyang and Dingxi in Gansu in the gully region and agricultural irrigation areas, and Erdos in Inner Mongolia in sandy areas.

The significant areas of vegetation cover corresponding to soil erosion was much lower than that of precipitation, including the north of Yulin, central part of Yan'an in Shaanxi, Luliang and Linfen in Shanxi in the hilly and gully region, small part in Qingyang and Guyuan in the gully regions of the Loess Plateau. To some degree, vegetation cover is closely controlled by the distribution of annual precipitation, the larger vegetation cover resulted from higher annual precipitation in disturbed ecosystem, which resulted in higher erosion-resistance due to the increased vegetation cover (Nunes *et al*., 2011; Xu, 2005).

3.4 The contribution of precipitation and vegetation cover responding to soil erosion

The variations of precipitation and vegetation cover had the significant impacts on the soil erosion on the Loess Plateau, as we mentioned above. However, the significant influences of precipitation and vegetation cover both existed in some areas. The contribution rates of precipitation and vegetation cover to soil erosion may be inconsistent. Therefore, we take a further step to quantify the relative contributions of precipitation and vegetation cover to soil erosion on the Loess Plateau.

On the whole, the contribution rate of precipitation showed the positive trend with the variation of soil erosion (Figure 8), which indicated that precipitation decrease reduced the Plateau's rainfall erosivity and eventually lowered soil loss. At the same time, vegetation cover increase also reduced the soil erosion due to its negative contribution rate (Figure 9), although the contribution rate of vegetation cover in most areas of the Loess Plateau was very low.

The areas affected remarkably by precipitation and vegetation cover mainly existed in hilly and gully region in the central and southwestern parts of the Loess Plateau. It was the region that suffered severe soil erosion and experienced the ecological restoration for Grain-to-Green Program. The contribution rate of precipitation in the hilly and gully region, such as Yulin, Yan'an in Shaanxi, and Luliang, Linfen in Shanxi, was mainly between 0.1 and 0.3 (Figure 8). The area in that region with contribution rate from 0.3 to 0.6 for precipitation was relatively small and scattered (Figure 8). However, the contribution rate of vegetation cover in these areas was higher than precipitation, especially along the main stream of the Yellow River (Figure 9). The absolute values of contribution rate for vegetation cover in the hilly and gully region were mainly higher than 0.3, and the areas with contribution rate more than 0.6 performed obviously (Figure 9). Therefore, the change of soil erosion in these areas predominantly related to the increased vegetation cover.

However, the areas in the gully region of the Loess Plateau, including Qingyang and Dingxi in Gansu and Guyuan in Ningxia, were more predominantly related to precipitation than to vegetation cover. The contribution rate of precipitation in most of these areas was mainly between 0.3 and 0.6 (Figure 8), while the absolute value of that for vegetation cover

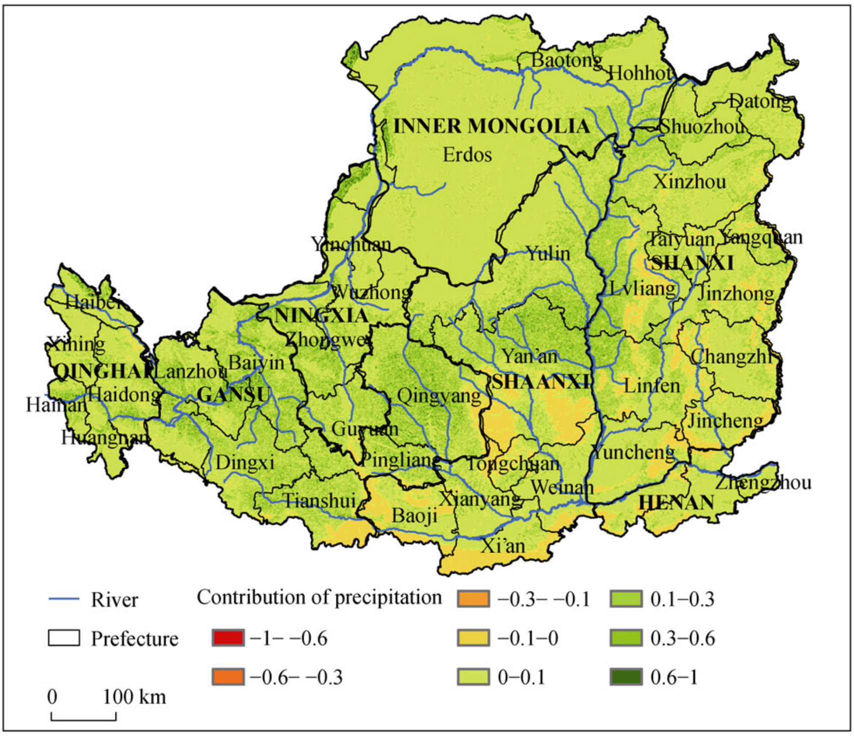

Figure 8 The relative contribution of precipitation ro soil erosion in 2000-2010 (the values ranging from 0 to 1)

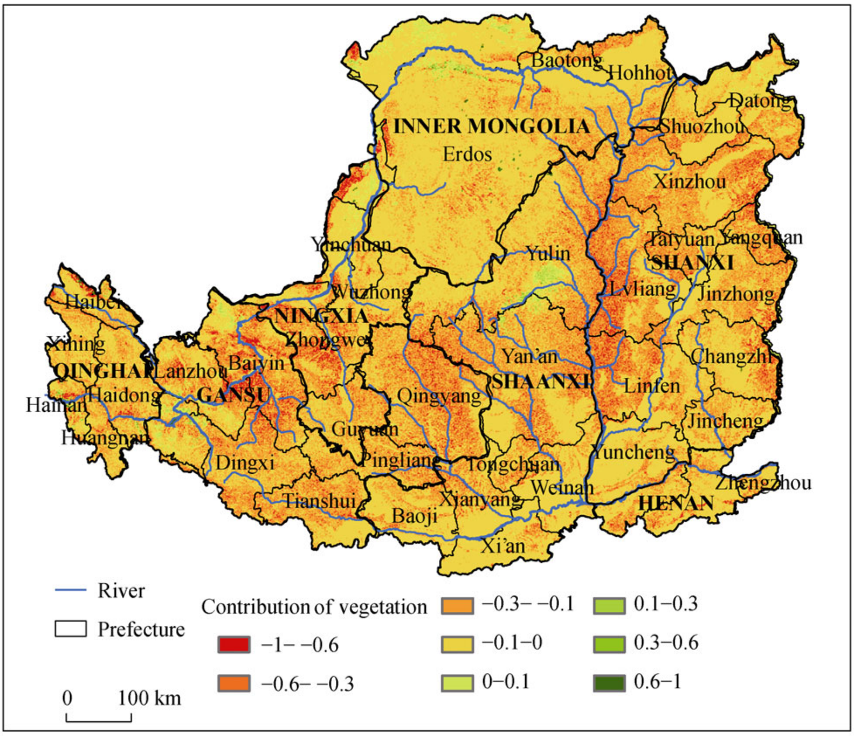

Figure 9 The relative contribution of vegetation to soil erosion in 2000-2010 (the values ranging from 0 to 1)

was less than 0.3 except some areas in the east of Qingyang in Gansu (Figure 9).

4 Conclusions

In recent decades, the soil erosion on the Loess Plateau showed a decreasing trend due to climate warming and drying and vegetation restoration. Great efforts have been made to enhance the vegetation restoration in the areas suffering from intense soil loss, which significantly reduced the soil erosion on the Loess Plateau.

(1) The average water erosion on the Loess Plateau between 2000 and 2010 was characterized as light. The more severe soil erosion with values more than 25 t hm^{-2} a^{-1} was mainly distributed in gully and hilly regions in the central, southwestern, and some earth-rocky mountainous areas. These areas suffering more severe soil loss on the Plateau reduced erosion at rates more than 1 t hm^{-2} a^{-1}, even more in Yulin, Yan'an, Luliang, Linfen and Qingyang prefectures where the soil erosion decreased at rates more than 3 t hm^{-2} a^{-1}.

(2) The contributions of precipitation and vegetation cover to the soil erosion on the Loess Plateau were assessed. Soil erosion intensity depended on both rainfall erosivity and erosion-resistance due to vegetation coverage. An increasingly abundant vegetation cover can better protect against soil erosion. Our results indicated that the soil erosion on the Loess Plateau was significantly declined for being benefited from the improved vegetation cover and ecological construction. These areas lied in the east of Yulin, most of the area of Yan'an prefecture in Shaanxi, and the west of Luliang and Linfen prefectures in Shanxi in the hilly and gully regions on the Loess Plateau and showed an evident erosion-resistance due to increase in the vegetation cover. The variation of vegetation cover responding to soil erosion showed the relatively higher contribution than the precipitation due to the soil and water conservation and ecological restoration. The achievement should be enhanced to ensure the sustainability of the Grain-to-Green Program in the Loess Plateau. However, some areas in Qingyang and Dingxi prefectures in Gansu and Guyuan in Ningxia were predominantly related to decreased precipitation, rather than by erosion-resistance of vegetation cover.

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