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Capacity of soil loss control in the Loess Plateau based on soil erosion control degree

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Abstract: The capacity of soil and water conservation measures, defined as the maximum quantity of suitable soil and water conservation measures contained in a region, were determined for the Loess Plateau based on zones suitable for establishing terraced fields, forestland and grassland with the support of geographic information system (GIS) software. The minimum possible soil erosion modulus and actual soil erosion modulus in 2010 were calculated using the revised universal soil loss equation (RUSLE), and the ratio of the minimum possible soil erosion modulus under the capacity of soil and water conservation measures to the actual soil erosion modulus was defined as the soil erosion control degree. The control potential of soil erosion and water loss in the Loess Plateau was studied using this concept. Results showed that the actual soil erosion modulus was 3355 $t·km^{-2}·a^{-1}$, the minimum possible soil erosion modulus was 1921 $t·km^{-2}·a^{-1}$, and the soil erosion control degree was 0.57 (medium level) in the Loess Plateau in 2010. In terms of zoning, the control degree was relatively high in the river valley-plain area, soil-rocky mountainous area, and windy-sandy area, but relatively low in the soil-rocky hilly-forested area, hilly-gully area and plateau-gully area. The rate of erosion areas with a soil erosion modulus of less than 1000 $t·km^{-2}·a^{-1}$ increased from 50.48% to 57.71%, forest and grass coverage rose from 56.74% to 69.15%, rate of terraced fields increased from 4.36% to 19.03%, and per capita grain available rose from 418 $kg·a^{-1}$ to 459 $kg·a^{-1}$ under the capacity of soil and water conservation measures compared with actual conditions. These research results are of some guiding significance for soil and water loss control in the Loess Plateau.

Keywords: Loess Plateau; soil erosion control degree; control potential of soil erosion and water loss; RUSLE

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1 Introduction

The Loess Plateau is located in the northern hinterland of China, and forms a significant portion of the Yellow River Basin. The major environmental problem in the Loess Plateau is serious soil erosion and water loss. According to the *Comprehensive Scientific Survey of Soil Erosion and Water Loss and Ecological Safety in China*, the Loess Plateau with a total area of 64×10^4 km^2 has soil erosion area up to 39×10^4 km^2, including severe water erosion area of 3.67×10^4 km^2 with soil erosion modulus $\geqslant$15,000 t·km^{-2}·a^{-1}, which accounts for 89% of similar areas in China (MWR, PRC *et al*., 2010). The serious soil erosion and water loss in the Loess Plateau restrains local socio-economic development and seriously threatens the flood control safety in the downstream channel, so it has attracted widespread attention from scholars at home and abroad; concentrated rainstorms, loose loess, low vegetation coverage, and unreasonable human activities are the main causes for the serious soil erosion in the Loess Plateau (Fu *et al*., 2011; Dotterweich, 2013; Sun *et al*., 2014; Wang *et al*., 2015; Zhao *et al*., 2014; Jiao *et al*., 2014).

To prevent the serious soil erosion and water loss, the Chinese government has taken a series of soil and water conservation measures, such as adjusting land use structure, recovering vegetation, improving tillage practice, building terraces on slopes, and constructing check dams in channels (Zhu, 2012; Bullock *et al*., 2011). As of 2010 (UMRYRAB, 2011), more than 90,000 check dams of various types had been constructed to form 28.63×10^4 ha of dam farmland, 281.85×10^4 ha of terraces had been built, and 968.28×10^4 ha of forest had been planted. The implementation of large-scale soil and water conservation programme has caused sharp decrease in sediment discharge in the Yellow River, for example, the average sediment discharge measured at Sanmenxia hydrologic station was 16×10^8 t during 1919–1960, but it was 6×10^8 t during 1990–2007, decreasing by 10×10^8 t, of which 50%–60% was caused by rainfall-induced sediment reduction and 40%–50% was caused by soil and water conservation measures (YRCC, MWR, 2013). The sediment reduction effect of soil and water conservation measures has been studied in depth by scholars from China and other countries; the soil conservation measures primarily include terracing, check dam building, and returning cultivated land to forest (grassland), and the study areas are mainly concentrated in the source region of centralized coarse sediments in the Hekou-Longmen section of the middle reaches of the Yellow River (Yao *et al*., 2013). Liu *et al*. (2014) believed that the sediment reduction effect of the level terraces in the Loess Plateau has been most probably underestimated, and the sediment reduction potential of ridged level terraces in the river basins can be up to 65%–90%; when the terrace percentage is more than 35%–40%, the sediment reduction effect of the terraces is basically stabilized at about 90%. Zhang *et al*. (2009) through study indicated that the influence degree of the human activities, including land use/cover changes, in the Hekou-Longmen section of the middle reaches of the Yellow River on the decrease in runoff in the river basin is over 50%. The construction of check dams has enabled significant change in the original relationship between sediment transport and sedimentation in the river basin. Research results show that, in natural conditions, the sediment delivery ratios of the river basins in the Loess Plateau are generally about 1, and decrease significantly with the construction of dam and reservoir projects, for example, the sediment delivery ratio in the Wuding River basin decreases to 0.2–0.4 (Xu *et al*., 2004).

The common index currently used for characterizing river basin governance degree is soil erosion and water loss governance degree (Su *et al*., 2011), namely, "ratio of the area of the regions with soil erosion and water loss governance measures taken to the area of the regions having soil erosion and water loss in a river basin (region)". However, governance degree cannot accurately reflect the governance level of a river basin; for some river basins, the soil erosion and water loss governance degree may have reached 100%, yet there are still soil erosion and water loss areas to be further governed, so the ratio of governance area to soil erosion and water loss area cannot comprehensively reflect the status of governance recovery (erosion control) of a small catchment. The slope farmlands account for about 2/3 of the total farmland area in the Loess Plateau, and are the main source of soil and water loss in the Loess Plateau, with average soil erosion modulus up to 25,000 $t\cdot km^{-2}\cdot a^{-1}$ (Gao *et al*., 2012). There are primarily two ways for converting the slope farmlands in the Loess Plateau: one is converting slopes into terraces, and the other is returning cultivated land to forest (grassland). There are currently few reports on soil and water conservation measures and slope farmland conversion potential in the Loess Plateau.

This paper, with the whole Loess Plateau as a study object, firstly defines the concept of soil erosion control degree and determines the calculation method for the capacity of soil and water conservation measures; secondly analyzes the capacity of soil and water conservation measures and the characteristics of soil erosion control degree of the whole Loess Plateau; and finally discusses the soil erosion and land use structure changes in the Loess Plateau under the capacity of soil and water conservation measures and analyzes the grain yield level in the Loess Plateau under the capacity of soil and water conservation measures. It is expected that the research results will provide scientific bases for soil and water conservation works in the Loess Plateau.

2 Materials and methods

2.1 Study region

The Loess Plateau is located between 100°52′–114°33′E and 33°41′–41°16′N, and contains seven provinces and autonomous regions, i.e., Qinghai, Gansu, Ningxia, Inner Mongolia, Shaanxi, Shanxi, and Henan, with a total area of 64.62×10^4 km^2. The Loess Plateau suffers very serious soil erosion and water loss, with complex and diverse erosion types. Soil erosion and water loss make up an area of 39.08×10^4 km^2, which includes water and wind erosion areas of 33.41×10^4 km^2 and 5.67×10^4 km^2, respectively.

The Loess Plateau surface is primarily covered by loess deposits (50–200 m deep) distributed in a relatively continuous manner, with high terrain in the northwest and low terrain in the southeast. Based on natural conditions, such as topography and geomorphology, as well as soil erosion features, the plateau can be zoned into six areas, namely, plateau-gully area, hilly-gully area, river valley-plain area, soil-rocky mountainous area, windy-sandy area, soil-rocky hilly-forested area (hereafter hilly-forested area for short) (Figure 1). The climate is continental monsoon, with rainstorms in the hot summer and autumn, and high winds and sand storms during the cold, dry winter and spring. The multi-year average temperature is 9–12°C, and multi-year average annual precipitation ranges from 200 to 700 mm from the northwest to the southeast; rainfall concentrations generally from June to September, with rainstorm in domination. The centralized precipitation accounts for over 60% of the annual total. There are 48 tributaries, each with an area over 1000 km^2, directly flowing into the Yellow River, with surface water in the whole region covering an area of 105.56×10^8 m^3. Vegetation can be divided into forest, forest-steppe, typical steppe, desert-steppe, and steppe-desert zones from the southeast to the northwest. The area is dominated by loessial soil, with a grain composition of fine sand and silt, a relatively uniform texture, and a loose, soft body with soil bulk density of 1.1–1.3 t/m^3 and total porosity of 50%–60%. Due to serious soil erosion and water loss, the soil is of relatively poor quality.

The Loess Plateau region incorporates 44 prefectures (cities) and 305 counties (banners) from seven provinces (autonomous regions). In 2011, the population density was 178.23 people·km^{-2} and the total population was 11517.52×10^4, including an agricultural population of 7547.37×10^4, accounting for 65.53% of the total population. The annual per capita net income for farmers is 3200 RMB yuan, and thus economic development is relatively low.

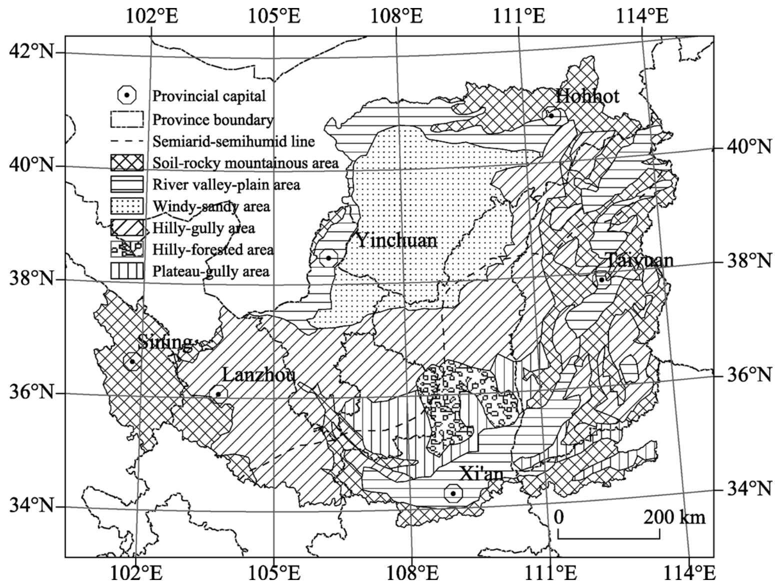

Figure 1 Zoning map of the Loess Plateau

2.2 Data collection and analysis

The digital elevation model (DEM) dataset was provided by the Geospatial Data Cloud, Computer Network Information Center, Chinese Academy of Sciences (http://www.gscloud.cn), and was obtained by processing the data from ASTER GDEM (V1), with projection type UTM/WGS84 and a spatial resolution of 30 m.

The soil type map was provided by the Cold and Arid Regions Sciences Data Center at Lanzhou (http://westdc.westgis.ac.cn), and included the China region subset of the Harmonized World Soil Database (HWSD) (Gunther *et al*., 2008). The data were in grid format. The spatial resolution was 1 km, the geographic coordinate system was WGS84, and the soil classification system used was FAO-90.

The land use data were from the 1:100,000 Land Use Database of China 2010, which was obtained using the human-computer interaction quick interpretation method on the basis of images from Landsat TM and Chinese environmental mitigation HJ1 satellite. Assessments showed that the classification accuracy of Class I land use types was 94% and that of Class II was 91% (Liu *et al.*, 2014). In this land use classification system, farmlands were divided into paddy field and dry farmland; in the Loess Plateau, dry farmlands were further divided into irrigated land, terraced field, dam farmland, and slope farmland. Data on the area of irrigated land were from agricultural statistical yearbooks of each county (NBS, PRC, 2012), and the terraced and dam farmland data were obtained from remote sensing and statistical investigation conducted by the Upper and Middle Yellow River Bureau, Yellow River Conservancy Commission (YRBMC, 2011).

The rainfall data were from the China Meteorological Data Sharing Service System (http://cdc.nmic.cn), and the 30 years of monthly precipitation data were collected from 108 state-level weather stations in and around the Loess Plateau.

Population data were obtained from the *Population Statistics for Counties and Cities of the PRC* (2011) published by the Administration Bureau for Public Order, Ministry of Public Security of the People's Republic of China. The farmland data and grain yield per unit area were obtained from statistical yearbooks, literature analysis and field questionnaires.

2.3 Analytical method

2.3.1 Concept of soil erosion control degree

Soil erosion control degree is the ratio of minimum possible soil erosion modulus to actual soil erosion modulus (Gao *et al.*, 2013), that is,

$$r = T_0 / T_s \tag{1}$$

where r is soil erosion control degree, dimensionless; T_0 is the minimum possible soil erosion modulus, that is, the soil erosion modulus under capacity of soil and water conservation measures, $t \cdot km^{-2} \cdot a^{-1}$; T_s is the actual soil erosion modulus, $t \cdot km^{-2} \cdot a^{-1}$. The soil erosion control degree is within 0–1, reflecting the degree of proximity to the ideal governance state of soil and water conservation; the closer the r is to 1, the higher the governance degree, and the closer the r is to 0, the lower the governance degree, that is, it deviates farther from the ideal governance state.

2.3.2 Capacity of soil and water conservation measures in the Loess Plateau

Capacity of soil and water conservation measures is defined as the maximum quantity of suitable soil and water conservation measures containable in an area, and it reflects the governance potential of soil and water conservation in an area. The concept of the capacity of soil and water conservation measures reflects the principle of "adaptation to local condition" in governance of soil and water conservation. According to the site requirements of different soil and water conservation measures, all suitable distribution zones of each measure are found, and then the soil and water conservation measures are laid out; after the measures are laid out, all governance works have been completed theoretically for the area, with the soil erosion modulus controlled at a reasonable level, and the quantity of soil and water conservation measures in this case is called capacity of soil and water conservation measures. Priority sequence should be taken into account in laying out soil and water conservation measures; in the Loess Plateau, the priority sequence is generally as follows: terrace → forestland → grassland. When a site meets the requirements for layout of all of the above three measures in the same time, the priority sequence is terrace, followed by forestland, and finally grassland.

(1) Suitable areas for terrace in the Loess Plateau

The loess region has thick soil layer, and slope-to-terrace is the main governance measure for gentle slope areas. The suitable areas for terrace in the Loess Plateau set in this paper meet the following conditions: original hilly-gully area and plateau-gully area used as farmlands shall have a slope less than 15°, while soil-rocky mountainous area, windy-sandy area, river valley-plain area and hilly-forested area shall have a slope less than 5° due to thinner soil layer.

(2) Suitable areas for forestland in the Loess Plateau

The growth of trees in the forestlands is primarily restricted by rainfall condition, and some scholars pointed out that the suitable areas for forest in the Loess Plateau should have more than 400 mm of precipitation but some others thought that the precipitation threshold for the suitable areas for forest should be 450 mm (Jiang, 1997; Li *et al*., 2008). The main landscape is steppe in semi-arid areas and forest steppe in semi-humid areas. Therefore, it was believed through this study that semi-humid areas and humid areas are suitable distribution areas for forestland, and semi-arid areas and arid areas are suitable distribution areas for grassland. For the semi-arid and semi-humid boundary, the climatic regionalization proposed by Zheng *et al*. (2010) was directly used in this paper. Consequently, the suitable distribution areas for forestland include: the existing forestlands; soil-rocky mountainous area, forested area, windy-sandy area and river valley-plain area having slope farmlands with slope more than 5° located in semi-humid areas; and hilly-gully area and plateau-gully area having slope farmlands with slope more than 15° located in semi-humid areas.

(3) Suitable areas for grassland in the Loess Plateau

In addition to the terraces and forestlands in the above areas, grasslands are laid out in other areas, so the suitable areas for grassland include: the existing grasslands; soil-rocky mountainous area, hilly-forested area, windy-sandy area and river valley-plain area having slope farmlands with slope more than 5° located in semi-arid areas; hilly-gully area and plateau-gully area having slope farmlands with slope more than 15° located in semi-arid areas; and sandy lands.

The layout area of the soil and water conservation measures in the above cases is called capacity of soil and water conservation measures, and the soil erosion modulus calculated on this basis is defined as minimum possible soil erosion modulus. The slopes were extracted using the digital elevation model (DEM) and subdivided into four classes, i.e., 0–5°, 5°–15°, 15°–25°, and >25°. The capacity of soil and water conservation measures in the Loess Plateau was obtained through discriminant analysis using the criteria function, under the support of the spatial model of the ERDAS IMAGINE9.1 software and with the existing land use map and climate zoning map. The terraces are 1229.31×10^4 ha, the forestlands are 1248.72×10^4 ha, and the grasslands are 3219.16×10^4 ha, accounting for 19.03%, 19.33%, and 49.82% of the total area of the Loess Plateau, respectively.

2.3.3 Determination of soil erosion modulus using RUSLE

The soil erosion modulus was determined using the revised universal soil loss equation (RUSLE) supported by the ArcGIS software (Kenneth *et al*., 1997), and the expression is:

$$A = R \cdot K \cdot S \cdot L \cdot C \cdot P \tag{2}$$

where A is the average annual soil loss, $t{\cdot}km^{-2}{\cdot}a^{-1}$; R is the rainfall-runoff erosivity factor, $MJ{\cdot}mm{\cdot}ha^{-1}{\cdot}h^{-1}{\cdot}a^{-1}$; K is the soil erodibility factor, $t{\cdot}ha{\cdot}h{\cdot}ha^{-1}{\cdot}MJ^{-1}{\cdot}mm^{-1}$; S is the slope steepness factor; L is the slope length factor; C is the cover-management factor; and P is the supporting-practice factor.

(1) Rainfall-runoff erosivity factor (R)

The empirical equation for rainfall erosivity with monthly precipitation, as proposed by Wischmeier *et al*. (1978), was used to calculate multi-year average rainfall erosivity:

$$R = \sum_{i=1}^{12} \left(1.735 \times 10^{1.5\times \lg \frac{P_i^2}{P} - 0.8188}\right) \quad (3)$$

where P and P_i are average annual and monthly precipitations, respectively, mm.

The multi-year average rainfall erosivity (R) value was calculated with Eq. (3) based on the monthly precipitation data collected in the study region; semivariance function simulation was conducted in GS+7.0 to find the optimal model. Kriging interpolation was carried out using the Gaussian model in the ArcGIS geostatistical module to obtain the rainfall erosivity factor of the whole Loess Plateau (Figure 2a).

(2) Soil erodibility factor (K)

Estimation of the soil erodibility (K) value was conducted with organic matter and particle composition of soil using the soil erosion-productivity impact calculator (EPIC) (Sharpley and Williams, 1990):

$$K = 0.1317*\{0.2+0.3\exp[-0.0256SAN(1-SIL/100)]\}*[SIL/(CLA+SIL)]^{0.3}*$$
$$\{1.0-0.25C/[C+\exp(3.72-2.95C)]\}*\{1.0-0.7SN_1/[SN_1+\exp(-5.51+22.9SN_1)]\} \quad (4)$$

where SAN is the sand fraction, %; SIL is the silt fraction, %; CLA is the clay fraction, %; C is the soil organic carbon content, %; and $SN_1 = 1-SAN/100$. The soil erodibility K value of the whole study region was calculated according to the soil type map and attribute data of the Loess Plateau (Figure 2b).

(3) Slope steepness and slope length factor (LS)

The LS calculation was based on the following expressions of McCool *et al*. (1989) used in the RUSLE:

$$S = 10.8\sin\theta + 0.03 \quad \theta < 9\% \quad (5)$$

$$S = 16.8\sin\theta - 0.5 \quad \theta \geqslant 9\% \quad (6)$$

$$L = (\lambda/22.1)^m \quad (7)$$

where λ is the horizontal projection length of the slope, m; m is the available length-slope exponent, and θ is the slope angle.

The LS factor values of the whole Loess Plateau were calculated using the LS factor calculation tool developed by Zhang *et al*. (2013), based on the 30 m DEM data of the Loess Plateau, with the whole Loess Plateau divided into eight sub-regions with the main rivers as boundaries (Figure 2c).

(4) Cover-management factor (C)

According to the research results from Zhang (2001, 2003) and Jiao *et al*. (2009) the C values of the main crops in the hilly-gully areas of the Loess Plateau are as follows: 0.28 for corn, 0.51 for beans, 0.47 for potatoes, and 0.53 for millet. The main crops in the gentle slope farmlands with slope less than 5° in the Loess Plateau are corn and wheat, whose C

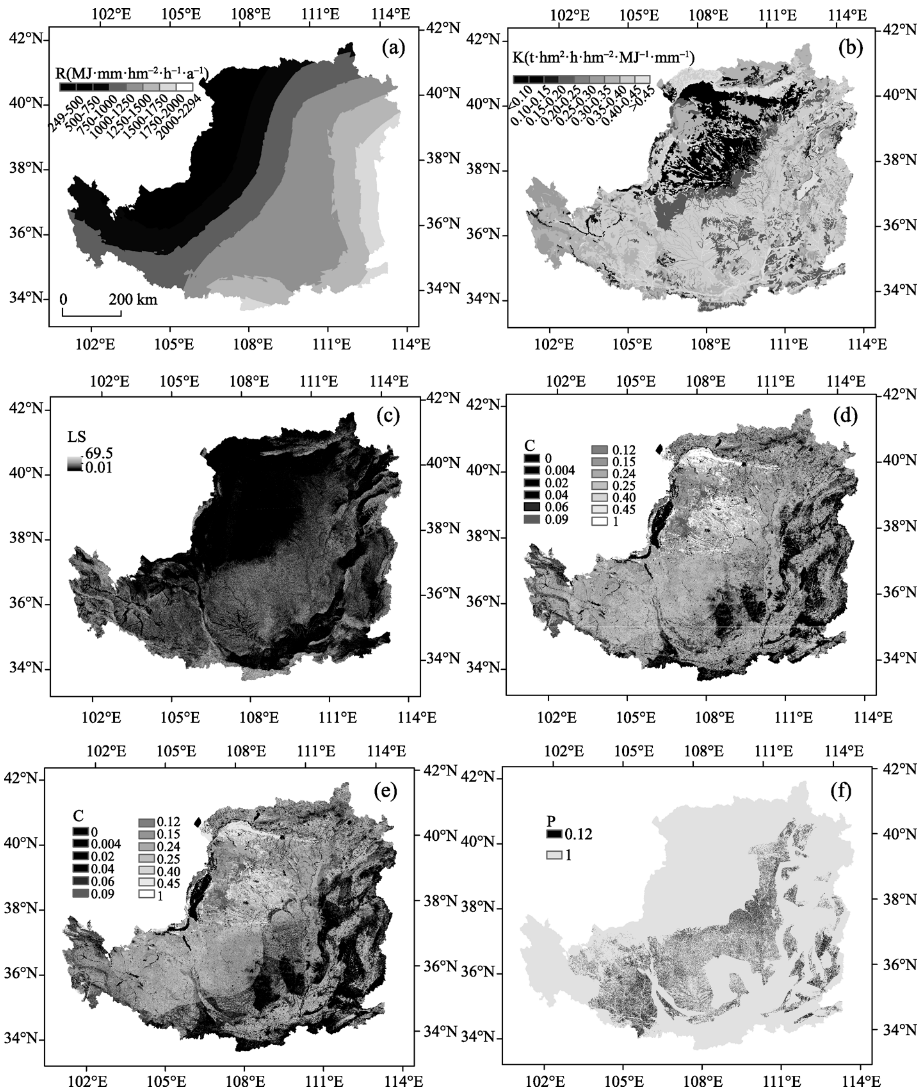

Figure 2 Various factor values from RUSLE for the Loess Plateau (a. rainfall erosivity factor (R); b. soil erodibility factor (K); c. slope length and steepness factor (LS); d. cover-management factor under actual conditions (C); e. cover-management factor under capacity of soil and water conservation measures (C); f. supporting-practice factor (P))

value is set as 0.25. The crops in the slope farmlands with slope more than 5° are dominated by beans, potatoes, and millet, and the C value is set as 0.40. The C value for paddy fields, water areas and building lands is set as 0, and that for unused lands is set as 1. For the forestlands and grasslands, the C values are taken from Table 1 depending on vegetation coverage. The C factor distribution map was obtained based on the land use type map of the Loess Plateau in 2010 (Figures 2d and 2e).

Table 1 C values at different vegetation coverage in the Loess Plateau

Vegetation coverage (%)	0–20	20–40	40–60	60–80	80–100
Forestland	0.25	0.12	0.06	0.02	0.004
Grassland	0.45	0.24	0.15	0.09	0.043

(5) Supporting-practice factor (P)

The soil layer is thick in most parts of the Loess Plateau, so terrace is the predominant slope governance measure. Based on the multi-site monitoring data acquired in the Loess Plateau, Ran *et al*. (2006) believed that rainfall of individual rain events with precipitation more than 100 mm and less than 200 mm can almost completely be retained by terraces without runoff generated. Terraces retain runoff to reduce the runoff scouring to slope surfaces and valleys, decreasing the soil erosion amount. The existing research efforts mostly focus on the "in situ" sediment reduction effect of terraces, that is, the sediment reduction amount of a plot after the slope is transformed into terraces. In addition, terraces have "ex situ" sediment reduction effect, which is primarily reflected in two aspects: one is that terraces can intercept the sediment-laden water flow from above, and the other is that the flow velocity of the slope runoff flowing through terraces will be lowered, thereby reducing the slope erosion amount below the terraces. Liu *et al*. (2014) thought that the sediment reduction effect of terraces has probably been underestimated for a long time due to the neglect of the "ex situ" sediment reduction effect of terraces. The spatial layout of terraces can also influence the sediment reduction benefit (Zhang *et al*., 2014), and terraces having the same area follow the law of "the upper part being better than the lower one" in respect of spatial layout. In other words, in respect of sediment reduction benefit, if terraces are laid out longitudinally in a river basin, they have better sediment reduction effect at the upstream than at the downstream; if terraces are laid out at one cross section, they have better sediment reduction effect at the upper area than at the lower area.

In the RUSLE, the Supporting-practice factor (P) is used to measure the influence of the soil and water conservation measures, including terraces, on the soil erosion. Research results show that (Wu *et al*., 2004; Liu *et al*., 2011), the sediment reduction benefit of the level terraces in the Loess Plateau could reach 88%, so the P value of the level terraces was taken as 0.12, and that of the other types of land was taken as 1 (Figure 2f). The existing land use data do not contain the spatial distribution information of terraces, but the area of terraces in all counties of the Loess Plateau can be obtained; therefore, some scholars (Xie, 2008) proposed to infer the factor of soil and water conservation measures (P) using the ratio of the area of terraces used to the total land area:

$$P=\left(1-\frac{S_t}{S}\times\alpha\right) \tag{8}$$

where S_t is the area of terrace, km^2; S is the total area of land, km^2; α is the sediment reduction benefit of terraces, taken as 0.12.

3 Results and analysis

3.1 Actual soil erosion modulus and minimum possible soil erosion modulus in the Loess Plateau

The calculated actual soil erosion modulus and minimum possible soil erosion modulus in the Loess Plateau are shown in Figure 3. In respect of spatial distribution, it can be seen that the areas with maximum actual soil erosion modulus and minimum possible soil erosion modulus are concentrated in the hilly-gully area and plateau-gully area in the hinterland of the Loess Plateau.

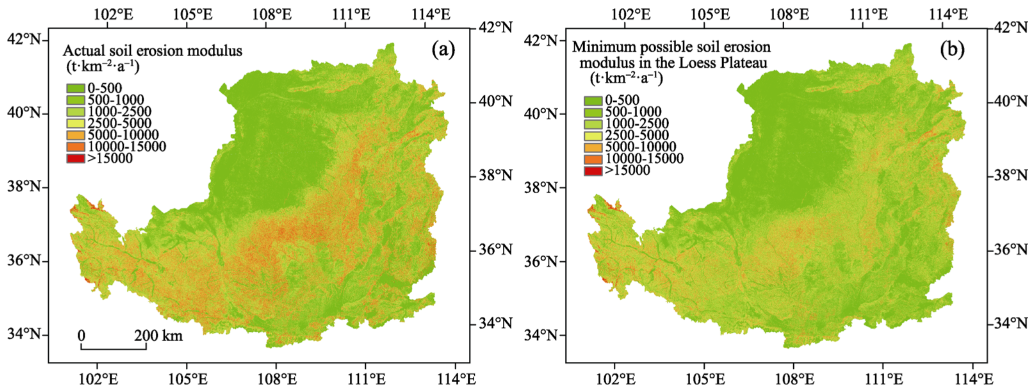

Figure 3 Actual soil erosion modulus and minimum possible soil erosion modulus in the Loess Plateau

Statistics was made for the average actual soil erosion modulus and minimum possible soil erosion modulus in various zoned areas using the Zonal Statistics tool in the ArcGIS (Table 2). For the whole Loess Plateau, the average actual soil erosion modulus is 3355 t·km^{-2}·a^{-1}, and the average minimum possible soil erosion modulus is 1921 t·km^{-2}·a^{-1}, decreasing by 42.74%. For different zoned areas, the plateau-gully area has the maximum decrease magnitude, which reaches 51.80%, whereas the river valley-plain area has the minimum decrease magnitude, which is 28.98%.

Table 2 Actual soil erosion modulus and minimum possible soil erosion modulus in all zones

Zoning	Actual soil erosion modulus (t·km^{-2}·a^{-1})	Minimum possible soil erosion modulus (t·km^{-2}·a^{-1})	Decreasing range (%)
River valley-plain area	1377	978	28.98
Windy-sandy area	465	311	33.12
Forested area	3436	1863	45.78
Hilly-gully area	4997	2477	50.43
Plateau-gully area	5417	2611	51.80
Soil-rocky mountainous area	3824	2650	30.70
Whole Loess Plateau	3355	1921	42.74

Soil loss tolerance refers to the maximum soil erosion intensity allowed for maintaining soil fertility and land productivity in a long period (Li *et al.*, 2005), and it is a criterion for judging whether soil and water loss occurs in an area; the soil loss tolerance currently used for the Loess Plateau is 1000 t·km^{-2}·a^{-1} (Zhang *et al.*, 2011). Areas with soil erosion modulus less than 1000 t·km^{-2}·a^{-1} are slight erosion areas, where no soil and water conservation measures need to be laid out in general; and areas with soil erosion modulus more than 1000 t·km^{-2}·a^{-1} are areas with light and more severe erosion, where soil and water conservation measures are generally needed. It can be seen from the statistics in Table 2 that, under the capacity of soil and water conservation measures, the minimum possible soil erosion modulus in the Loess Plateau is still greater than the soil loss tolerance in the region. The authors made statistics for the percentages of the slight erosion areas and the light and more severe erosion areas under the actual condition and the capacity of soil and water conservation measures respectively (Table 3). Under the actual condition, the percentages of the slight erosion areas and the light and more severe erosion areas in the Loess Plateau are 50.48% and 49.52%, respectively; under the capacity of soil and water conservation measures, the percentage of the slight erosion areas increases to 57.71%, while the percentage of the light and more severe erosion areas decreases to 42.29% accordingly.

Table 3 Ratios of different erosion types under actual conditions and under capacity of soil and water conservation measures

Zoning	Under the actual condition (%)		Under capacity of soil and water conservation measures (%)	
	Slight erosion	Light or above	Slight erosion	Light or above
River valley-plain area	72.89	27.11	75.90	24.10
Windy-sandy area	87.27	12.73	90.38	9.62
Forested area	45.16	54.84	52.77	47.23
Hilly-gully area	31.66	68.34	43.57	56.43
Plateau-gully area	37.38	62.62	46.58	53.42
Soil-rocky mountainous area	40.81	59.19	46.94	53.06
Loess Plateau	50.48	49.52	57.71	42.29

3.2 Soil erosion control degree of the Loess Plateau

The soil erosion control degree of the whole Loess Plateau was calculated according to the concept of soil erosion control degree (Figure 4), and the average soil erosion control degree of the Loess Plateau is 0.57, belonging to moderate governance level. The areas with high governance degree are the river valley-plain area, soil-rocky mountainous area, and windy-sandy area, with soil erosion control degrees of 0.71, 0.69, and 0.67, respectively. The soil erosion control degrees of the hilly-forested area and hilly-gully area are 0.54 and 0.50, respectively, belonging to moderate governance level. Nevertheless, the plateau-gully area has relatively low governance degree, with soil erosion control degree of 0.48 (Figure 4).

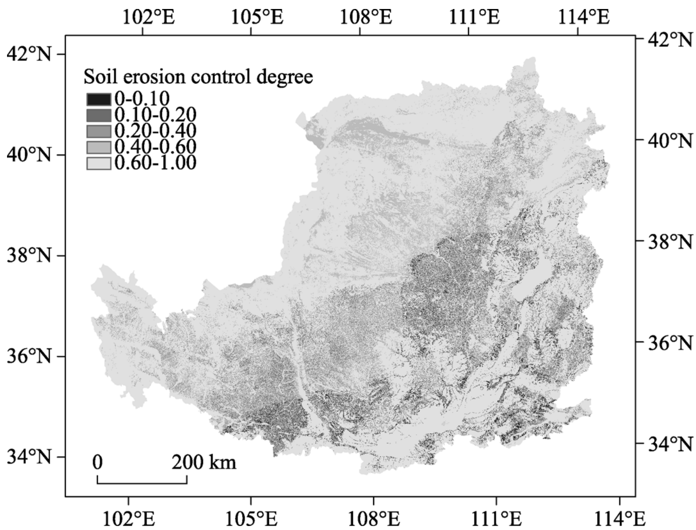

Figure 4 Soil erosion control degree in the Loess Plateau

3.3 Land use changes under actual condition and capacity of soil and water conservation measures

Statistics was made for the land use structure in the whole Loess Plateau under the actual condition and the capacity of soil and water conservation measures, respectively (Table 4). Under the actual condition, the percentages of terrace, slope farmland, forestland, and grassland in the Loess Plateau are 4.36%, 22.35%, 14.99%, and 41.75%, respectively. Nevertheless, under the capacity of soil and water conservation measures, the percentages of terraces, slope farmland, forestland, and grassland are 19.03%, 0.00%, 19.33%, and 49.82%, respectively. In the whole Loess Plateau, the percentage of the terrace area is increased from 4.36% under the actual condition to 19.03% under the capacity of soil and water conservation measures, and the forest and grass coverage is increased from 56.74% to 69.15%.

Table 4 Land use structure under actual condition and under capacity of soil and water conservation measures in the Loess Plateau

Land use type	Under the actual condition		Under capacity of soil and water conservation measures	
	Area (10^4 ha)	Percentage (%)	Area (10^4 ha)	Percentage (%)
Paddy field	58.75	0.91	58.74	0.91
Irrigated land	288.72	4.47	288.72	4.47
Dam farmland	28.63	0.44	28.63	0.44
Terrace	281.85	4.36	1229.31	19.03
Slope farmland	1443.91	22.35	0.00	0.00
Forestland	968.28	14.99	1248.72	19.33
Grassland	2697.69	41.75	3219.16	49.82
Others	693.63	10.73	388.18	6.01

3.4 Grain yield change under capacity of soil and water conservation measures

According to the land use interpretation results and the terrace and check dam survey data (YRBMC, 2011), there were 58.75×10^4 ha of paddy field, 288.72×10^4 ha of irrigated land, 28.63×10^4 ha of dam farmland, 281.85×10^4 ha of terraces, and 1443.91×10^4 ha of slope farmland in total in the Loess Plateau in 2010. The average per unit yields were 12,000 $kg\cdot ha^{-1}$ for paddy field, 6500 $kg\cdot ha^{-1}$ for irrigated land, 4500 $kg\cdot ha^{-1}$ for dam farmland, 2100 $kg\cdot ha^{-1}$ for terraces, and 1050 $kg\cdot ha^{-1}$ for slope farmland, respectively. Calculation based on this shows that the total grain output in the Loess Plateau under the actual condition is 4818.51×10^4 t, and that the slope farmland accounts for 2/3 of total area of farmlands but they contribute only 1/3 to the grain yield. The total population in the Loess Plateau was $11{,}517.52\times10^4$ in 2010, so the per capita grain available under the actual condition was 418 $kg\cdot a^{-1}$. Under the capacity of soil and water conservation measures, the areas of paddy field, irrigated land and dam farmland did not change, but the area of terraces increased to 1229.31×10^4 ha and that of slope farmland decreased to 0; the calculated total grain yield in the Loess Plateau increased to 5291.95×10^4 t, and the per capita grain available could increase to 459 $kg\cdot a^{-1}$.

3.5 Influence of check dams on erosion-induced sediment yield

Check dams are main gully governance works in the Loess Plateau, and the suitable scale of check dams under the capacity of soil and water conservation measures was not taken into account. The reason is that check dams have less influence on erosion but much influence on sediment yield. The influence of a check dam on soil erosion is primarily reflected in two aspects: one is shortening the slope length to “submerge” the bared slope areas with great soil erosion modulus in the lower part of the river basin, and to reduce the soil erosion amount in the controlled areas. The other is retaining water and sediment to decrease the flow rate of gully runoff and thus to reduce scouring downstream check dams. The influence of the siltation by a check dam on the slope soil erosion can be evaluated using the established typical slope in hilly-gully area of the Loess Plateau and the RUSLE (Figure 5).

According to the calculation results in section 2.3.2, the rainfall-runoff erosivity (R) of the Loess Plateau was taken as 1265 $MJ·mm·ha^{-1}·h^{-1}·a^{-1}$. The soil erodibility (K) was taken as 0.040 $t·ha·h·ha^{-1}·MJ^{-1}·mm^{-1}$. The LS factor was calculated with Eqs. (5), (6) and (7). The C values for dam farmland, terraces, slope farmland, and grassland were taken as 0.25, 0.40, 0.40, and 0.09, respectively. The factor of soil and water conservation measures (P) for terraces was taken as 0.12.

Under the typical slope conditions shown in Figure 5, if there is no dam farmland (Figure 5a), the soil erosion modulus is 5617 $t·km^{-2}·a^{-1}$ in the area above the hillock borderline, below which the soil erosion modulus is 8528 $t·km^{-2}·a^{-1}$, and the average soil erosion modulus of the slope is 6864 $t·km^{-2}·a^{-1}$. If there is a dam farmland (Figure 5b), and it is assumed that the siltation thickness in the dam farmland is 4.2 m, then the area of the dam farmland accounts for 4.76% of the total area, thus in the area above the hillock borderline, the soil erosion modulus does not change, still being 5617 $t·km^{-2}·a^{-1}$, but below the hillock borderline, it decreases to 7153 $t·km^{-2}·a^{-1}$, and the average soil erosion modulus of the slope decreases to 6275 $t·km^{-2}·a^{-1}$. Compared with the soil erosion modulus in the case without dam farmland, the soil erosion modulus has a decrease magnitude of 8.58%, which is relatively low.

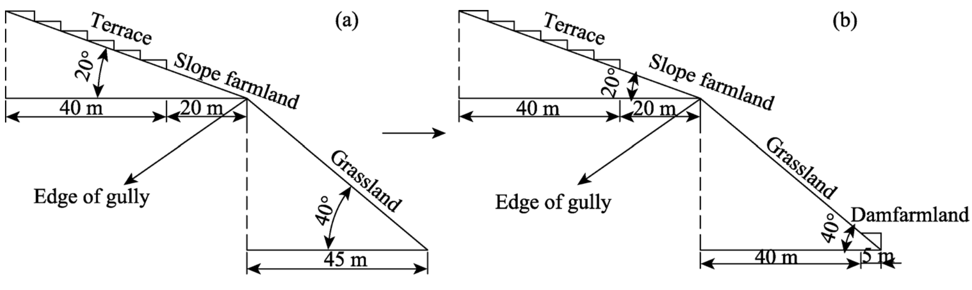

Figure 5 Effect of deposition of check dams on slope soil erosion (a. without dam farmland, b. with dam farmland)

The sediment delivery ratio (SDR) can reflect the influence of soil and water conservation measures, including check dams, on sediment transport process. In natural condition, the SDR in loess hilly-gully areas is generally close to 1. The SDRs in typical river basins were calculated, based on the collected siltation data of key dams in the typical river basins in the middle reaches of the Yellow River, as well as the configuration ratios and control area ratios of the key dams, medium-sized dams and small-sized dams (Table 5). The results show that, the SDRs in the typical rivers in the middle reaches of the Yellow River decrease to about 0.62.

Table 5 Sediment delivery rate in the major rivers at the middle reaches of the Yellow River

River (hydrometric station)	Sediment load (10^4 t)	Deposition (10^4 t)	Erosion (10^4 t)	SDR
Tuwei river (Gaojiachuan)	1713.51	271.09	1984.60	0.70
Dali river (Suide)	2174.56	1119.47	3294.03	0.56
Jialu river (Shenjiawan)	875.37	223.42	1098.79	0.64
Chabagou river (Caoping)	71.75	131.40	203.15	0.33
Wuding river (Baijiachuan)	4930.95	5555.41	10486.36	0.44
Gushanchuan river (Gaoshiya)	1208.44	298.25	1506.70	0.59
Huangfuchuan river (Huangfu)	3203.57	193.59	3397.16	0.87
Kuye (Wenjiachuan)	6779.99	274.16	7054.15	0.82

4 Discussion and conclusions

4.1 Discussion

Compared with soil and water loss governance degree, soil erosion control degree can better reflect the actual governance level of a river basin, and is applicable to slope scale, river basin scale and region scale. On the slope scale, the change in soil erosion amount was simulated under different slope governance conditions by establishing a theoretical model for slopes (Gao *et al*., 2012), thereby the slope governance approach of the minimum possible soil erosion modulus was determined, and with the existing slope governance being taken into account, the slope governance degree can be determined. On the small catchment scale, finer land use classification results can be obtained. For example, QuickBird images can be used to accurately identify the distribution of terraces and slope farmlands (Li *et al*., 2015), and even to obtain the changes of terrain caused by soil and water conservation measures, which may lead to the change in LS factor (Gao *et al*., 2013). In addition, on the slope and small catchment scales, it is even simpler and more accurate to determine the capacity of soil and water conservation measures. Therefore, the capacity of soil and water conservation measures can be used to rapidly evaluate the governance degrees of slopes and small catchments. On the river basin and region scales, the key to calculating soil erosion control degree is to reasonably determine the capacity of soil and water conservation measures. For the whole Loess Plateau, research efforts on the suitability of forestland are currently relatively weak, so scientifically identifying suitable areas for forestland can improve the calculation accuracy of soil erosion control degree.

Soil erosion control degree is based on the concept of soil erosion modulus, so it is very important to accurately calculate soil erosion modulus. There are many methods for determining soil erosion modulus, e.g., use of measured runoff sediment data, rainfall simulation, field survey, radioactive isotope, and mathematical model. The RUSLE was used for calculating soil erosion modulus in this paper; although the limitation to application of the RUSLE in the Loess Plateau was corrected to the maximum extent possible, the calculated erosion amount still has some deviation due to weak research efforts on the C value in China. Moreover, the RUSLE can only be used to calculate water erosion modulus, but some parts of the Loess Plateau belong to wind erosion areas, and there is currently lack of an effective calculation model for complex soil erosion modulus for wind erosion and water erosion, so the change in wind erosion modulus was not taken into account in this study, resulting in too small soil erosion modulus calculated in windy-sandy areas.

4.2 Conclusions

The average soil erosion modulus under actual condition in the whole Loess Plateau is 3355 $t\cdot km^{-2}\cdot a^{-1}$, the average minimum possible soil erosion modulus is 1921 $t\cdot km^{-2}\cdot a^{-1}$, and the soil erosion control degree is 0.57, belonging to moderate level. In respect of zoned areas, the areas with high governance degree are the river valley-plain area, soil-rocky mountainous area, and windy-sandy area, whereas the hilly-forest areas, hilly-gully area, and plateau-gully area have lower governance degrees. In respect of river basins, the Dahei River, the Huangfuchuan River, the Qingshui River, the Kuye River and the Pianguang River basins have higher soil erosion control degrees, whereas the Qingjian River, the Wuding River, the Jialu River and the Yanhe River basins have lower soil erosion control degrees.

Comparison between the actual condition and the capacity of soil and water conservation measures shows that the percentage of slight erosion areas in the whole Loess Plateau is increased from 50.48% under the actual condition to 57.71% under the capacity of soil and water conservation measures. The forest and grass coverage is increased from 56.74% under the actual condition to 69.15% under the capacity of soil and water conservation measures. The per capita grain available is increased from 418 $kg\cdot a^{-1}$ under the actual condition to 459 $kg\cdot a^{-1}$ under the capacity of soil and water conservation measures.

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