Heliyon 5 (2019) e02985

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Spatial and temporal characteristics of soil conservation service in the area of the upper and middle of the Yellow River, China

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ARTICLE INFO

Keywords:
Ecology
Environmental science
USLE
Ecosystem service
The area of the upper and middle of the Yellow River (AUMYR)
Soil conservation (SC)

ABSTRACT

Soil erosion is an important environmental problem in the area of the upper and middle of the Yellow River (AUMYR), China, one of the most severe soil erosion areas in the world. It is significantly influences on the ecological security and sustainable development of the region. Soil conservation (SC) service, as one of the most important regulating services provided by ecosystems, can alter soil and water processes and improve ecosystem services that ensure human welfare. Investigations of spatial and temporal characteristics of SC service play important roles in soil erosion control and ecosystem protection in AUMYR. In the past several years, restoration projects (e.g. the Grain-for-Green project) were implemented to improve SC in most of AUMYR. It is needed to evaluate the change of SC service brought about by the projects. This study carries out quantitative spatial analysis of SC services through Universal Soil Loss Equation (USLE) model and geographic information system (GIS) manipulation based on various datasets, such as remote sensing image, digital elevation model (DEM), climate, and land use/cover maps. Soil retention calculated as potential soil erosion (erosion without vegetation cover) minus actual soil erosion was applied as indicator for SC service. The results are like these. (1) The total amount and mean capacity of SC service in AUMYR were 7.22 billion t/a and 142.2 t/hm^2·a in 2000 and 10.19 billion t/a and 200.8 t/hm^2·a in 2010, respectively. South-east AUMYR exhibited a much higher capacity of soil retaining than the north-west. (2) Forest ecosystems displayed higher SC capacity than other types of ecosystems. Moreover, the SC capacity of ecosystems increased with the increasing of slope gradient. (3) Variations of SC rate (the ratio of SC to potential soil erosion in percentage) in different units (ecosystem, slope zone and city) were relatively small and ca. 90% of potentially eroded soil was retained in AUMYR. (4) The spatial characteristics of SC service in AUMYR were primarily controlled by topography at the regional scale. Vegetation cover restoration significantly improved the capacity of SC service in AUMYR in the midst year of 2000 and 2010. The results revealed that ecological restoration efforts significantly enhanced SC service of ecosystem in the study area.

1. Introduction

Ecosystem services (ESs) are the benefits that people obtain from nature (Daily, 1997; Costanza et al., 1997; MA, 2005). It has been recognized that the ESs are the basis of human survival and development (Ouyang and Zheng, 2009). Since the 1990's, ESs have been one of up-to-date research fields in ecology and the related disciplines.

Valuation of ESs can play an important role in conservation planning and ecosystem-based management. In the past two decades, ecological valuation of ESs is becoming increasingly critical to understand the multiple benefits provided by ecosystems. Tremendous progress has been made in this field (Egoh et al., 2009; Su et al., 2012; Su and Fu, 2013; Guerra and Pinto-Correia, 2016; Yang and Tang, 2019), especially after Costanza et al. (1997) established a milestone in ESs research by conducting the evaluation of nature's services in 1997. In order to inform and

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https://doi.org/10.1016/j.heliyon.2019.e02985
Received 27 November 2018; Received in revised form 8 February 2019; Accepted 2 December 2019

direct agencies responsible for ES management, Egoh et al. (2009) mapped the production of five ESs (*i.e.* surface water supply, water flow regulation, soil accumulation, soil retention, and carbon storage) in South Africa. Su et al. (2012) evaluated four kinds of ESs (*i.e.* net primary production (NPP), carbon sequestration and oxygen production, water conservation and soil conservation sediment control, water yield) in the Yanhe watershed on the Loess Plateau, China and proposed sustainable ecosystem management suggestions in the region. Su and Fu (2013) estimated three types of ES (*i.e.* sediment control, water yield, and NPP) in the Chinese Loess Plateau under climatic and land use changes. To disclose the relationship between farm management and ES provision, Guerra and Pinto-Correia (2016) studied the challenges and opportunities for soil erosion prevention in Mediterranean silvo-pastoral systems, and their results can also be used to support land management and policy design.

Though multiple ESs were quantitatively assessed in these mentioned literatures and this quantification of ESs may improve the ecosystem-based management practices and support policy-making to address the challenges of the sustainable use of natural resources, these evaluated multiple ESs are still only a portion, and they cannot reflect the total ESs of terrestrial ecosystems. Thus, above all elaborate efforts can be conducted to estimate an individual ES. When a framework was established for one kind of ES (e.g. soil erosion control), the principle may be applied to other regulating services (e.g. flood control, carbon fixation et al.). Notably, few evaluations on a single type of ES are reported. There is still a lack of scientific studies on a specific ES in depth.

Studying the relationship between ESs and spatial-temporal pattern of ESs relationship is of great significance for promoting the further development of ESs research. ESs are complex and diverse, and the relationship between ESs may evolve over time (Rodríguez et al., 2006; Zheng et al., 2014). The tradeoffs and synergies of ESs are a key point of the relationship between multiple ESs (Feng et al., 2017; Geng et al., 2019), and they have obvious and complex scale effects (Xu et al., 2017; Feng et al., 2017). And that the main emphases of ESs research have shifted from ESs assessment (Costanza et al., 1997; Sheng et al., 2010; Fu et al., 2011; Guerra et al., 2016) to analyzing the relationship between multiple ESs (Hu et al., 2019; Wu and Li, 2019) in recent years. But studies on trade-offs and synergies of multiple ESs are mostly in the qualitative description stage and lack of quantitative research with spatial location information at present. This relationship is affected by land use and climate change (Fu et al., 2015; Jiang et al., 2016; Bai et al., 2019), and the quantitative relationship between them is less known.

Clarifying the spatial-temporal characteristics of each ES is the basis for studying the relationship between multiple ESs and for understanding the connotation of ES. Soil conservation (SC) service, as one of the most important regulating services provided by ecosystems, guarantees the ecological security and sustainable development of a region. Over the past few years, several studies have been implemented to evaluate the ES of SC (Fu et al., 2011; Rao et al., 2014, 2016; Guerra et al., 2014, 2016; Guerra and Pinto-Correia, 2016; Syrbe et al., 2018). Fu et al. (2011) evaluated the SC service of ecosystems distribution and change in the Loess Plateau of China and found that ecosystem SC service had been improved from 2000 to 2008 as a result of vegetation restoration. Rao et al. (2014) studied the spatial patterns and impacts of SC service in China and found that the spatial characteristics of SC in China were primarily controlled by climate and terrain at the national scale. This work focused on the capacity for ES provision of SC and provided a static figure which did not consider the temporal variation of SC. Guerra et al. (2014, 2016) established a conceptual framework for the mapping and assessment of regulating ESs (soil erosion prevention) in Portugal, and the actual ES provision and the capacity for ES provision was differentiated in their studies. Rao et al. (2016) valuated the variation of ES of SC in recent ten years and its driving factors in Southwestern China, and their achievement enhanced the understanding of the effects of ecological restoration programs. But the spatial and temporal of the actual ES provision was not mentioned in this work.

Most of these SC service valuations above mentioned are based on the Universal Soil Erosion Equation (USLE) (Wischmeier and Smith, 1978). The USLE has been widely used all over the world for its simple structure and ease of use. When combined with GIS, the USLE has the capability of spatial analysis and large-scale applicability (Van der Knijff et al., 1999; Rao et al., 2014). These SC service assessments are generally on a watershed (e.g. Su et al., 2012), a geomorphic unit (e.g. Fu et al., 2011) or on a whole country (e.g. Rao et al., 2014). Actually, regional management is often carried out on the administrative divisions in China.

Soil erosion is a major threat to the continued provision of ESs in the area of the upper and middle of the Yellow River (AUMYR), one of the most severe soil erosion regions in the world (Fu et al., 2011; Chen et al., 2015; Wang et al., 2015). The Yellow River was the most sediment-laden river in the world, and 90% of the sediment load was from AUMYR (Wang et al., 2015). In the past several decades, restoration programmes were carried out to abate the intense soil erosion in AUMYR (Shi et al., 2016). The Grain for Green Project — implemented by the Chinese government in 1999 was the recent and most successful one of them. This project has increased vegetation coverage on the Loess Plateau (Chen et al., 2015) and led to a sharp decrease in runoff and sediment discharge (Shi and Wang, 2015). It is needed to evaluate the change of soil erosion control service resulted from this revegetation programme. The spatial patterns and impacts of SC service are of great importance in soil and water conservation planning. Accordingly, assessment and enhancement of SC service in AUMYR will be critical to controlling soil erosion and ensuring ecological security. AUMYR will be an important development area in China for its abundance of mineral resources. How to coordinate the contradiction of development and environment protection in this area is a confronting issue. In this study, we implemented the SC service of ecosystems in AUMYR at the regional scale on a GIS platform with the USLE model. Several aims of this study (1) to reveal the spatial distribution of SC service; (2) to investigate the SC service in different units (ecosystem types, cities and slope zones); (3) to analyze the influence factors on the spatial characteristics of SC service; (4) to analyze the impact factors on the variation of SC service in the county level in recent ten years, are integrated in this work.

2. Materials and methods

2.1. Study area

The area of upper and middle of the Yellow River (AUMYR) locates in the middle-west of China (97°10′–112°43′E, 33°35′–42°47′N). Administratively it relates to four provinces (i.e. Shaanxi, Shanxi, Ningxia and Inner Mongolia) and consists of 19 cities (i.e. Wuzhong, Zhongwei, Yinchuan, Shizuishan, Alashan, Wuhai, Baoyannaoer, Ordos, Baotou, Yulin, Yan'an, Weinan, Tongchuan, Xianyang, Baoji, Xinzhou, Lvlliang, Linfen, Yuncheng) (Figure 1). The central government of China subjectively delineated five regions as typical key development zones for development in 2000. AUMYR is one of them. So AUMYR is not a district compartmentalized by basin. AUMYR is about 50.6×10^4 km^2. The area crosses three kinds of climatic zones (*i.e.* semi-humid, semi-arid, and arid). The average annual precipitation in the area is 383 mm and ranges between 44.8 mm–835.7 mm (1953–2010) and it decreased from southeast to northwest. The rainfall concentrated through June to September (60–80%). Droughts frequently occurred in most of AUMYR in history and this meteorological disaster is extremely harmful to this area. In recent half century, the mean annual temperature fluctuated between -2.35 °C–14.55 °C. During the past half century, the extreme minimum temperature reached to -44.8 °C (Jan. 15^{th} 1958, Wutai Mountain station) and the extreme maximum temperature attained to 44.8 °C (July 24^{th} 1988, Guaizi Lake station). The temperature in this area has similar spatial variability trend with that of rainfall. Aeolian sandy soil and loamy loessal soil are the main soil types in AUMYR. Besides these, there are other soil types distributed in this area, such as calcareous alluvial soil, salinized fluvo aquic soil and calcareous skeletal

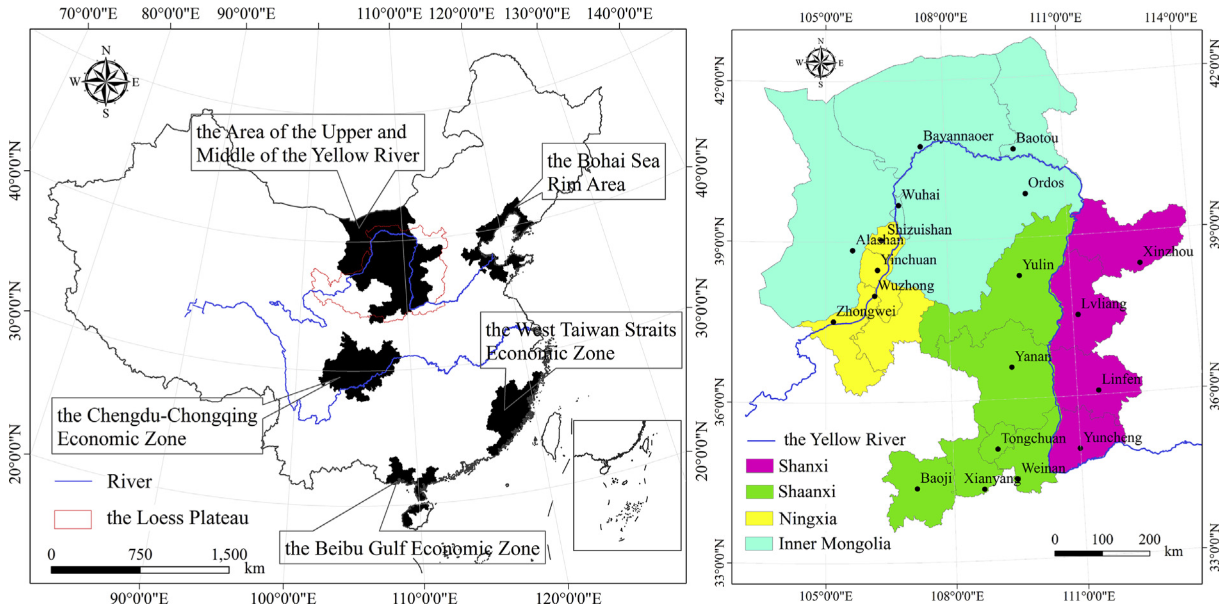

Figure 1. Location map of the study area.

soil etc (Meng, 2006). Most of AUMYR (67%) distributed in the elevation of 1000–1500 m and more than half of the area located in the slope of less than 5° (57.4%). In this region, most big tributaries flow into the Yellow River, such as Weihe, Fenhe, Wudinghe, Yanhe, Beiluohe, etc.

AUMYR have abundant resources (coal, oil, natural gas etc.) and mineral resources in AUMYR occupy an important position in China. The area has proven coal reserves of 5.7×10^{11} tons. It is the main coal-producing area and most of the coal produced transferred out of the district (Zhou et al., 2013). China will focus on the development of the energy and heavy chemical key industries (*i.e.* coal chemical industry, energy power etc.) in AUMYR. AUMYR will be a typical area of dependent resources to promoting economic growth and be one of the five key development areas (the Chengdu-Chongqing Economic Zone, the West Taiwan Straits Economic Zone, the Beibu Gulf Economic Zone, the Bohai Sea Rim area and AUMYR) in China (Figure 1).

2.2. Data source

Daily rainfall data provided by the National Meteorological Information Centre of China (http://cdc.cma.gov.cn) from 74 meteorological stations in and around the AUMYR were used to analyze the spatiotemporal variation of rainfall erosivity on the study area during the period 2000–2010. Soil organic carbon data were collected from the Second Soil Investigation in China. A conterminous China multi-layer soil particle-size distribution (sand, silt and clay content) dataset was developed according to the 1:1, 000, 000 scale soil map of China from the Second National Soil Survey (downloaded from Resources and Environmental Science Data Center, Chinese Academy of Sciences, http://www.resdc.cn). The K factor value was calculated with soil properties (soil organic carbon and soil particle-size distribution). The DEM Dataset used in the study, with a resolution of 30 m, was downloaded from the International Scientific and Technical Data Mirror Site, Computer Network Information Center, Chinese Academy of Sciences (http://datamirror.csdb.cn). LS factors were calculated using this DEM dataset. Ecosystem classification data in 2010 were derived from the Landsat TM/ETM and HJ-1 satellite data at a spatial resolution of 30 m (Wu et al., 2014). These dataset was collected from the China National Land Cover Data for 2010 (ChinaCover2010) (http://www.chinacover.org.cn), and the ecosystems were classified into six categories in this study, including woodland, grassland, wetland, cropland, residential area and desert. The maximum 16-day NDVI (Normalized Differential Vegetation Index) data in 2010 derived from MODIS images were obtained from the NASA EOS DATA Gateway (http://wist.echo.asa.gov/api) (250 m resolution). The data used in this study could be simply grouped into spatial data and statistics. All the spatial data were retained or resampled to 250 m resolution map using a nearest neighbor method.

2.3. Methods

The soil conservation (SC) of ecosystems can be described as soil retention, which is the difference between potential and actual soil erosion, with the USLE model being used. Soil retention is calculated as soil erosion without vegetation cover and soil erosion control practice minus that under the current land use/land cover pattern and soil erosion control practice (Fu et al., 2005). The models are presented as follows:

$$\text{Actual soil erosion rate} = \text{RKLSCP} \quad (1)$$

$$\text{Potential soil erosion rate} = \text{RKLS} \quad (2)$$

$$\text{SC} = \text{Potential soil erosion rate–Actual soil erosion rate} = \text{RKLS (1–CP)} \quad (3)$$

$$\text{SC rate} = \frac{\text{SC}}{\text{Potential soil erosion rate}} \times 100\% = (1 - \text{CP}) \times 100\% \quad (4)$$

where, R is the rainfall erosivity factor (MJ·mm/hm^2·h·a); K is the soil erodibility factor (t·hm^2·h/hm^2·MJ·mm); LS is the slope length factor (L) and slope steepness factor (S); C is the vegetation cover factor, which refers to the protection of soil by ecosystems in this study. P is the soil conservation practice. LS, C and P are dimensionless.

2.3.1. Rainfall erosivity factor (R)

The R-factor quantifies the effect of rainfall impact and also reflects the amount and rate of runoff likely to be associated with precipitation events (Wischmeier and Smith, 1978). There are 74 meteorological stations in or near AUMYR. We adopted annual rainfall erosivity at these stations of 2000 and 2010, which was calculated using the daily rainfall erosivity model (SCO, 2010; Rao et al., 2014), the latest progress in rainfall erosivity research in China. The model can be described as:

$$\overline{R} = \sum_{k=1}^{24} \overline{R_k} \quad (5)$$

$$\overline{R_k} = \frac{1}{N}\sum_{i=1}^{N}\left(\alpha\sum_{j=1}^{m}P_{dij}^{\beta}\right) \quad (6)$$

$$\alpha = 21.239\beta^{-7.3967} \quad (7)$$

$$\beta = 0.6243 + \frac{27.346}{\overline{P_d}} \quad (8)$$

$$\overline{P_d} = \frac{1}{n}\sum_{l=1}^{n}P_{dl} \quad (9)$$

where, $\overline{R}$ is the mean annual rainfall erosivity (MJ·mm/hm^2·h·a); $\overline{R_k}$ is the mean rainfall erosivity in the k-th half month; P_{dij} is the daily precipitation (mm) on the j-th day of the k-th half month in the i-th year; $\alpha$and β account for regression coefficients; $\overline{P_d}$ is the mean daily precipitation; P_{dl} is the daily precipitation on the l-th day in the study period; k represents the order of 24 half months for a year ($k = 1, 2, \ldots, 24$); i represents the order of years in the study period ($i = 1, 2, \ldots$, N); j represents the order of days in the k-th half month of the i-th year ($j = 1, 2, \ldots$, m); and l represents the order of days in the entire study period ($l = 1, 2, \ldots$, n). Note that only days with precipitation greater than or equal to 12 mm are included.

The R-factor map layer of the study area was created using a kriging interpolation in GIS (spatial resolution of 250 m).

2.3.2. Soil erodibility factor (K)

Soil erodibility describes the susceptibility of soil particles to detachment and movement by water, and reflects the sensitivity of soils to erosion. In this study, the value of the K-factor was calculated using the equation of Sharply and Williams (1990):

$$\mathrm{K} = \left\{0.2 + 0.3\exp\left[-0.0256S_d\left(1-\frac{S_i}{100}\right)\right]\right\} \times \left(\frac{S_i}{Cl+S_i}\right)^{0.3} \times \left[1.0 - \frac{0.25C}{C+\exp(3.72-2.95C)}\right] \times \left[1.0 - \frac{0.7SN}{SN+\exp(-5.51+22.9SN)}\right] \quad (10)$$

where S_d, S_i, Cl, and C are the percentage contents of sand, silt, clay, and organic carbon, respectively. SN equates to $1–S_d/100$. This equation results in a K factor with units of (short ton)·acre·hour· (100feet·(short ton)·acre·inch)$^{-1}$, thus the result was divided by 0.1318 to obtain the equivalent value in SI units. The data on soil mechanical composition and soil organic carbon were collected from Soil Species in China (Meng, 2006). Then the K factor value was assigned to different soil types. There is no soil on water surface, and then zero was assigned to water body. The results of the soil erodibility map were converted into grid format for further analysis. Figure 2 illustrates the spatial distribution of the soil erodibility factor K.

2.3.3. Topographical factor (L, S)

The topography affects the runoff characteristics and transport processes of sediment. The topographical factor LS indicates the impact of length and slope of terrain on soil erosion. This study used a DEM (30 m resolution) and Remortel et al. (2001) LS factor calculation program to calculate the LS factor. The calculation program was developed in ARC Macro language (AML) by ArcInfo workstation.

2.3.4. Vegetation cover factor (C)

Soil loss is significantly related to vegetation coverage. Van der Knijff et al. (1999) developed a method for C factor estimation using NDVI with NOAA AVHRR remote sensed data expressed as formula (11). After several experiments, they assigned the values of 2 and 1 to parameters of α and β respectively to soil erosion prediction in European continent. Van Leeuwen and Sammons (2004) considered that 2.5 and 1 are the more reasonable values with parameters of $\alpha$and β when using the MODIS-NDVI data.

$$C = \exp\left[-\alpha\cdot\frac{NDVI}{\beta - NDVI}\right] \quad (11)$$

In this study, C factors of 2000 and 2010 were calculated using NDVI derived from MODIS image with $\alpha = 2.5$ and $\beta = 1$.

2.3.5. Soil conservation practice (P)

As to P factor, it is difficult to reflect the results of soil and water conservation measures (such as growing terrace, and contour tillage) with land use maps at large scale (Fu et al., 2005). Slope gradient is a key factor for the soil loss on AUMYR. For this reason, the slope-based Wener method (Lufafa et al., 2003; Fu et al., 2005) was applied to calculate P factor. And the equation was:

$$P = 0.2 + 0.03 \times S \quad (12)$$

where S is the slope grade (%).

2.4. Data processing

Spatial Analyst tools in ArcGIS were employed to reveal the spatial distribution of SC service in 2000 and in 2010, with different cities (Wuzhong, Zhongwei, Yinchuan, Shizuishan, Alashan, Wuhai, Baoyannaoer, Ordos, Baotou, Yulin, Yan'an, Weinan, Tongchuan, Xianyang, Baoji, Xinzhou, Lvlliang, Linfen, Yuncheng), ecosystems (woodland, grassland, wetland, cropland, residential area and desert), slope zones (<5°, 5°–8°, 8°–15°, 15°–25°, 25°–35°, >35) considered. The mean capacities and total amounts of SC service in corresponding units were consequently calculated. For the purpose of exploring the relationship between SC service and soil erosion risk, we performed Pearson Correlations using SC capacities (SC; Eq. (3)) and potential soil erosion rates (Eq. (1)). We also employed a stepwise regression between SC and impact factors (climate, soil, terrain, and vegetation, represented by the R, K, LS, C and P factors, respectively) to reveal their relative contribution on influencing the spatial characteristics of SC service. All statistical analyses mentioned in this section were performed at the county level. There are 167 counties in the study area. Every county boundary was used as a mask to extract the result distribution map, and then we can get the corresponding value (R, K, LS, C, P, SC et al.) of each county.

3. Results

3.1. Distribution of actual soil erosion in AUMYR

The spatial distribution of annual rainfall erosivity (R factor) of AUMYR was shown in Figure 2, and the annual R value was 580.5 MJ mm/hm^2·h·a in 2000 and 868.0 MJ mm/hm^2·h·a in 2010, respectively. The spatial distribution of the R values displayed a significant decreasing trend from the southeast to the northwest of AUMYR, ranging from 49.5 MJ mm/hm^2·h·a to 2669.8 MJ mm/hm^2·h·a in 2000 and from 107.7 to 3463.5 MJ mm/hm^2·h·a in 2010. The map of K values in Figure 2 was generated to show the spatial distribution of soil erodibility, and the average K factor of AUMYR was 0.0379 t hm^2·h/hm^2·MJ·mm, varying from 0.0123 t hm^2·h/hm^2·MJ·mm to 0.0589 t hm^2·h/hm^2·MJ·mm. The slope steepness and slope length (LS) factor values in Figure 2 ranged from 0 to 125.8 with mean values of 3.1984. The areas with higher LS values were located in the hilly and gully regions and the mountainous area with steep topography in AUMYR, which indicates that these regions were topographically prone to erosion. The vegetation cover factor (C) map was shown in Figure 2. The average C value was 0.5333 in 2000 and 0.4545 in 2010 in AUMYR. The spatial distribution of the C factor

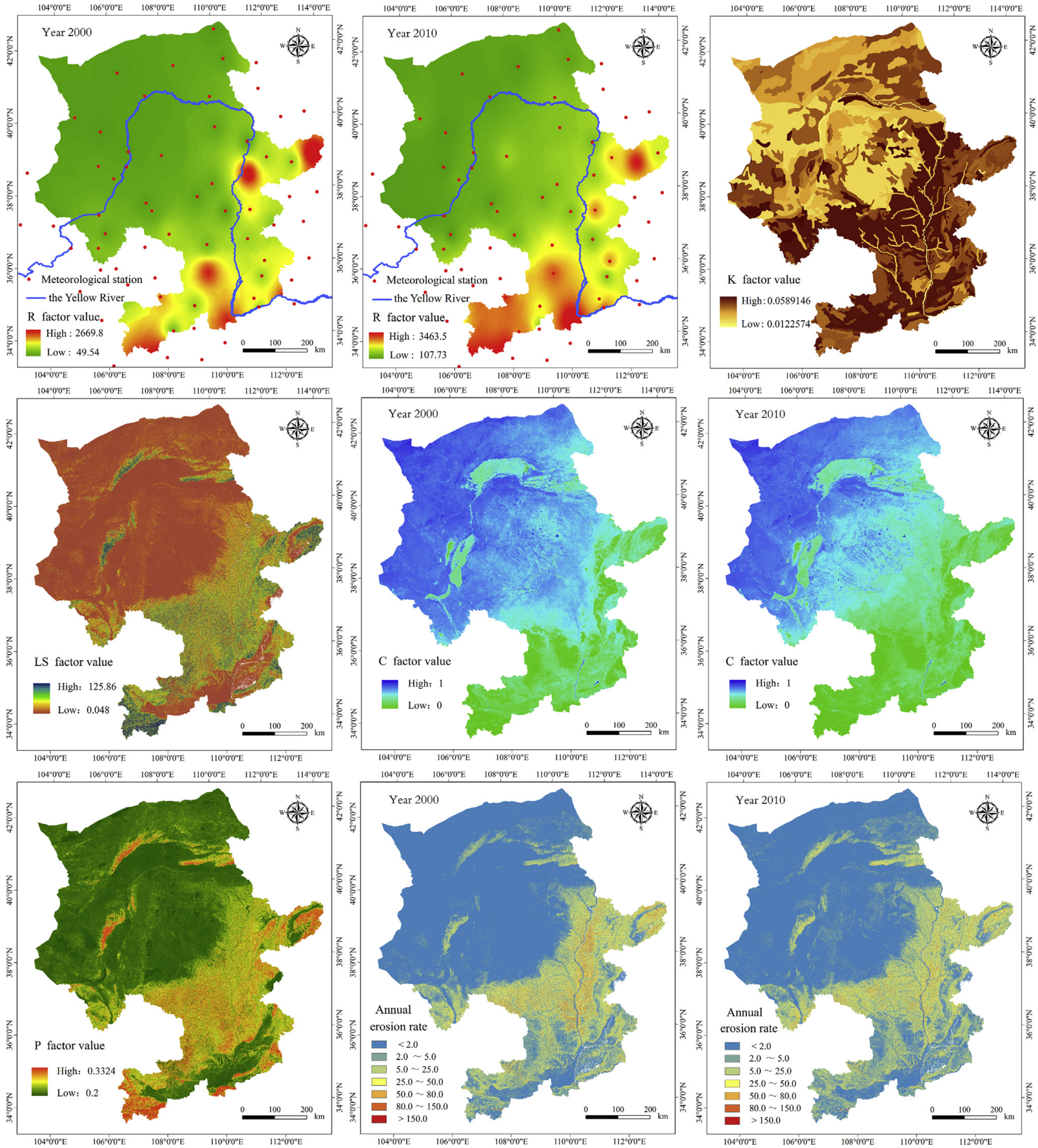

Figure 2. Spatial distribution of USLE factors and the estimated actual soil erosion rate.

showed an increasing trend from the southeast to the northwest of the study area. The average P value was 0.2036 in AUMYR.

The actual soil erosion rate predicted by the USLE model based on the factors mentioned above in AUMYR was 7.47 t/hm^2·a in 2000 and 6.48 t/hm^2·a in 2010. Severe soil erosion mostly occurred in the middle of AUMYR and some mountainous areas (Figure 2). These results agreed well with the general descriptions from the Ministry of Water Resources of China (2011). Therefore, we could confirm that USLE and its parameters used here were able to simulate general soil erosion conditions in AUMYR. Indirectly, the model of the SC service could also be considered reasonable.

3.2. Distribution of SC in AUMYR

3.2.1. General spatial-temporal SC services distribution

The potential and actual annual soil erosion amount were calculated to be 7.60 billion t and 0.38 billion t in 2000, and 10.52 billion t and 0.33 billion t in 2010, respectively. Thus, the total amount of soil retained were 7.22 billion t in 2000 and 10.19 billion t in 2010, with a mean capacity of 142.2 t/hm^2 in 2000 and 200.8 t/hm^2 in 2010, respectively. The SC service displayed heterogeneity in terms of its spatial distribution, with south-east of AUMYR generally performing much better than the north-west (Figure 3). Ecosystems with a great capacity (>1000 t/hm^2·a) were primarily located in the Wutai Mountains and the mountain areas of southern Baoji City, Weinan City and south-central of AUMYR. Great capacity of SC (>1000 t/hm^2·a) with 3.08% of the total area retained 35.89% of the total amount of soil retained in 2000 and with 5.55% of the total area retained 49.39% of the total amount of soil retained in 2010.

3.2.2. Distribution of SC service in different ecosystem types

Comparisons among ecosystems (Figure 4) showed that woodland displayed the highest SC capacity, followed by cropland, and then grassland. With regard to quantities, grassland and woodland retained (~77% of the total) much more soil than other ecosystems.

3.2.3. Distribution of SC service in different slope zones

Comparisons among slope zones (Figure 5) showed that SC capacity of ecosystems increased with the increasing of slope gradient, and the mean SC capacity of slope zone of >35°reached to 475.9 t/hm^2·a in 2000 and 629.1 t/hm^2·a in 2010. With regard to quantities, ecosystems with slope zones of 15–25° and 8–15°retained (~62% of the total) much more soil than other slope zones.

3.2.4. Distribution of SC service in different cities

Comparisons among cities (Figure 6) indicated that Baoji City had the highest SC capacity, followed by Tongchuan, Yan'an, Linfen, and Xinzhou. With regard to the total amount, ecosystems in Yan'an, Baoji, and Xinzhou contributed most, accounting for 20.66%, 18.46%, and 11.61%, respectively, of the total. The accumulative proportion would reach to 70% when the cities of Lvliang and Linfen were added, while the sum of area ratio was less than a quarter.

3.2.5. Distribution of SC service in different cities

The SC capacity displayed a significant positive correlation with potential soil erosion rate in 2000 (n = 167, r = 0.999, $p < 0.001$) and in 2010 (n = 167, r = 0.999, $p < 0.001$), which was determined by climate, soil, and terrain. Where the risk of soil erosion is high, the capacity of SC for an ecosystem is considerable.

3.2.6. Characteristics of SC rate in AUMYR

Changes of SC rate in different units (ecosystems, slope zones and cities) were relatively small (Figure 7). The mean SC rate in whole AUMYR was 89.0% in 2000 and 90.6% in 2010. In terms of ecosystems, woodland had the highest SC rate and desert had the lowest SC rate. As far as cities concerned, Baoji, Tongchuan, Xianyang had the highest SC rates in AUMYR. SC rate tended to increase with the increase of slope steepness.

3.3. Impact factors on SC

The spatial distribution characteristics of SC service are determined by the interactions of impact factors (natural and anthropogenic). The Pearson Correlations of SC and R, K, LS, C and P are 0.708, 0.269, 0.895, -0.624 and 0.849 (all correlations are significant at the $p < 0.01$ level, n = 167) in 2000, and the corresponding Pearson Correlations are 0.689, 0.292, 0.883, -0.665 and 0.842 ($p < 0.01$, n = 167) in 2010. The stepwise regression indicated that, the LS factor could explain most variance in SC, with the variance contribution (VC) reaching 80.1% in 2000 and 78.0% in 2010. The VC values of the other factors were relatively small.

4. Discussion

4.1. Model simulations of soil erosion rate and SC service

All factors used in the USLE were computed for AUMYR using local data. We analyzed relevant research progress during the process of parameter localization, and simulated soil erosion rates as well as SC capacities using relatively reasonable parameter models. In this study, the actual soil erosion rate calculated by the USLE was 7.47 t/hm^2·a in 2000 and 6.48 t/hm^2·a in 2010. This result of year 2010 gives good agreement with the survey data (0.289 billion t in 49.15 × 10^4 km^2 of the Yellow River basin in 2010) issued by the Ministry of Water Resources of China et al. (2010). Sun et al. (2014) predicted soil erosion for

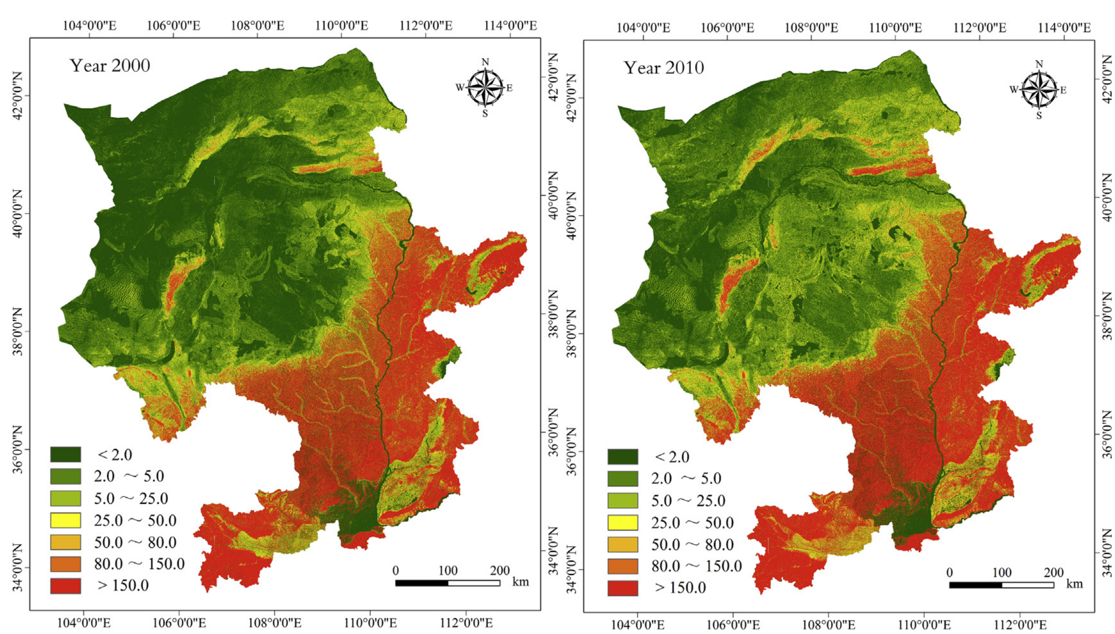

Figure 3. Spatial distribution of ecosystem SC services (t/hm^2·a).

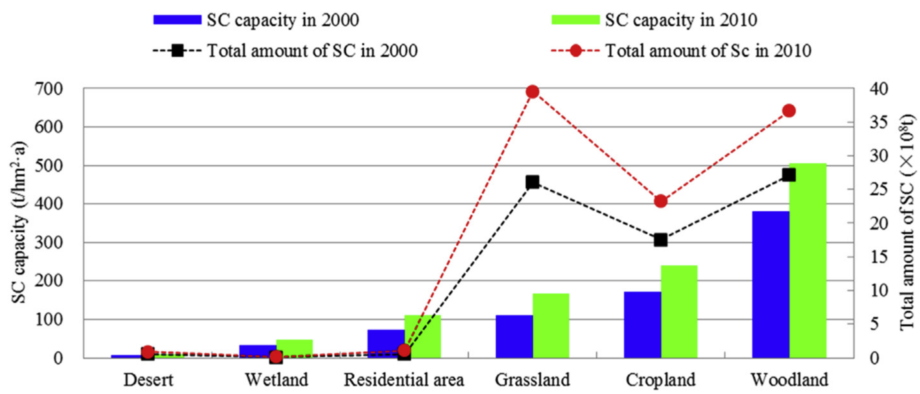

Figure 4. Distribution of SC service in different ecosystem types.

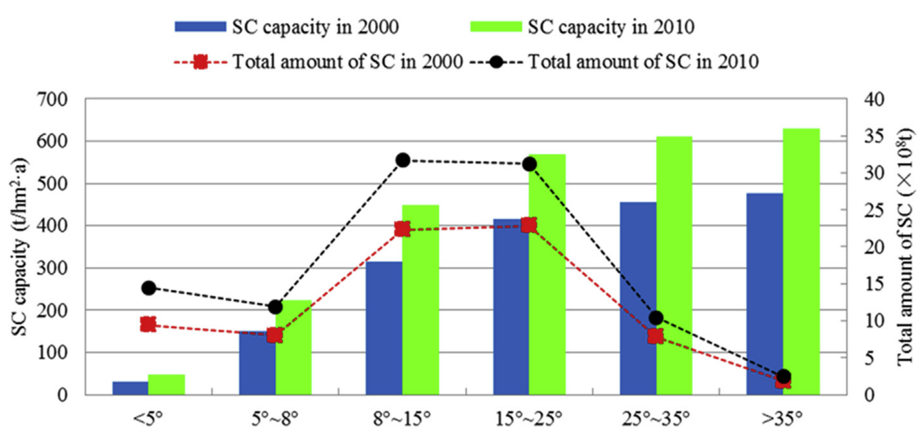

Figure 5. Distribution of SC service in different slope zones.

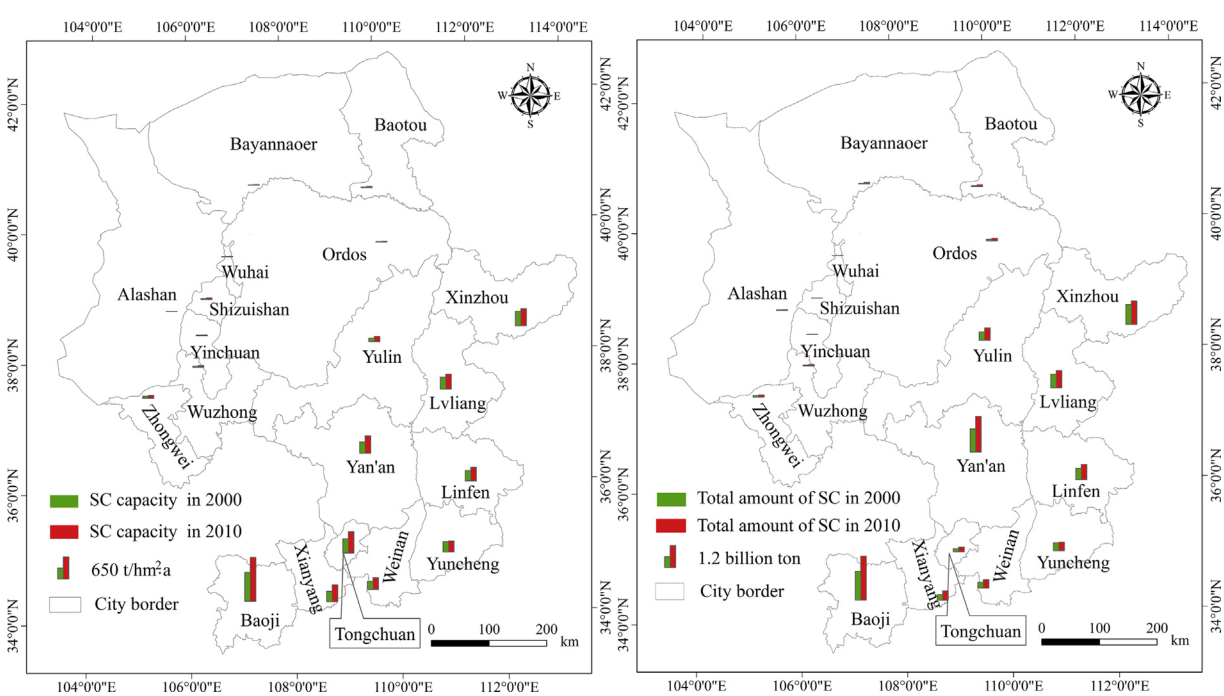

Figure 6. Distribution of SC service in different cities.

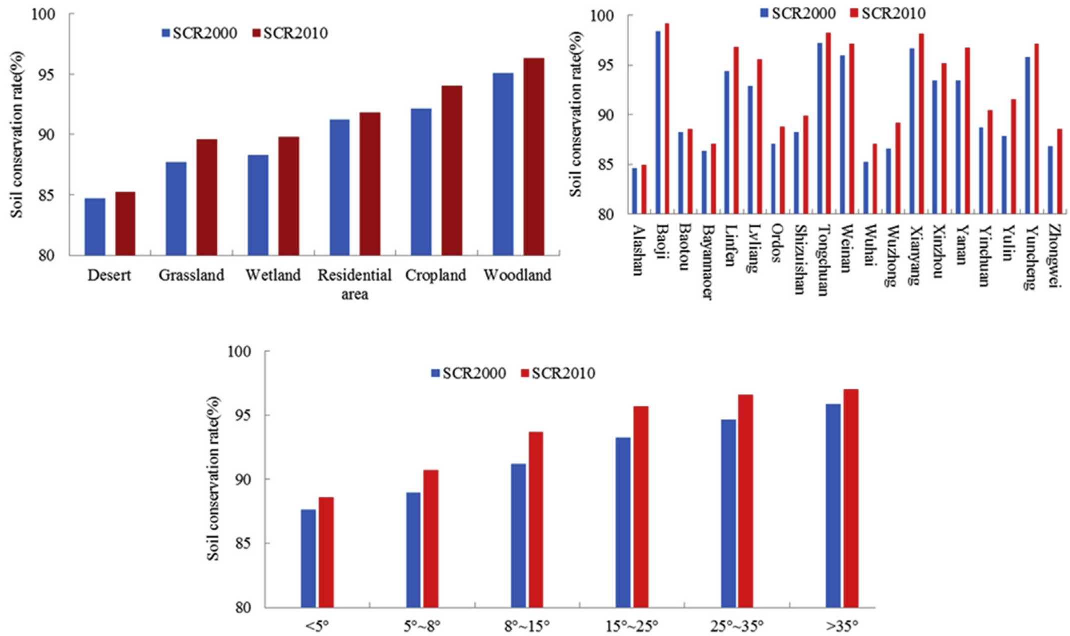

Figure 7. SC rate in different ecosystems, cities and slope zones.

2000–2010 on the Loess Plateau was 15.2 t/hm^2·a with 1 km resolution spatial data. Fu et al. (2011) also modeled soil erosion change during 2000–2008 on the Loess Plateau and found that soil erosion rate decreased mainly for the Grain for Green Project. So the result of soil erosion rate simulated by Sun et al. (2014) in 2010 should be less than 15.2 t/hm^2·a. Through these comparisons, we reasonably believe that the USLE model and the parameters used herein proved capable of realistically simulating the soil erosion situation in AUMYR, thus bringing about a satisfactory accuracy to the evaluation of SC service.

As is stated above, topography (LS factor) is the most important impact factor for SC in AUMYR. Sun et al. (2014) modeled the result with spatial dataset of 1 km resolution. In our study, a spatial resolution of 30 m was used. From Eq. (3), we concluded that the higher SC was smoothed away. At the same time, we reasonably believe that the result data (0.289 billion t in 49.15 × 10^4 km^2 of the Yellow River basin in 2010) issued by the Ministry of Water Resources of China used the coarse resolution data, and this leading to our result (soil erosion rate) is a little higher than that of it.

4.2. Characteristics of SC service

The total amount of soil retained by ecosystems was 7.22 billion t/a in 2000 and 10.19 billion t/a in 2010, with a corresponding mean capacity of 142.2 t/hm^2·a and 200.8 t/hm^2·a, respectively. Rao et al. (2014) estimated the mean capacity of SC at the national scale and found that SC of China was 224.42 t/hm^2·a in recent years. Vegetation cover plays an important role in SC. AUMYR is located at the northwest of China. Generally the vegetation coverage of AUMYR is less than that of south and east of China. Thus the mean capacity of SC in AUMYR a little less than the result of Rao et al. is reasonable. Moreover, our result was well consistent with the SC capacity of forests (380.5–505.5 t/hm^2·a) and grasslands (111.4–167.5 t/hm^2·a) that was determined through surveys and syntheses (Ouyang et al., 1999).

The ecosystems' SC service in AUMYR was distributed unevenly for different sections. The south-eastern of AUMYR displayed a much higher SC capacity than the north-west. This distribution pattern is agreement with the result of Fu et al. (2011). The spatial distribution of SC is quite similar to those of precipitation (Xin et al., 2011) and vegetation coverage. The Pearson Correlation of SC and R, C implied a potential influence of climate and vegetation. Ecosystems located in the cities of Baoji, Tongchuan, Yan'an, Linfen, and Xinzhou have higher soil erosion control further verified this for these cities located in the south-east of AUMYR and they have relatively high precipitation and good vegetation coverage. The SC of different ecosystems (woodland, cropland and grassland) predicted was consistent with the result of Sun et al. (2014) by and large.

At the same time, ecosystems located in the higher slope zones demonstrated excellent soil erosion control capacity. Ecosystems with a great SC capacity (N > 1000 t/hm^2·a) were primarily located in the mountain areas (loess hilly area, Wutai Mountains, and the mountain areas of southern Baoji City and Weinan City). Stepwise regression further demonstrated that the spatial patterns of SC service in AUMYR were dominantly controlled by topography at the (city) county scale. This result coincided with the result of Sheng et al. (2010) and was partly agreement with the result of Rao et al. (2014). Rao et al. found out that the spatial patterns of SC service in China were primarily controlled by two factors: climate and terrain, at the national scale. The differences of climate at the regional scale are not prominent with those at the national scale. Therefore, climate was not the controlling factor of SC capacity in AUMYR.

Based on the positive correlation between SC service and soil erosion risk, greater importance should be given to higher erosion risk areas (Rao et al., 2014), since the state of ecosystems in these areas could be fairly critical to the actual soil erosion. Overall, SC rates were high and the difference of SC rates in different units was relatively small in AUMYR. These results matched well with the results of Sun et al. (2014). And this displayed that the ecosystems in AUMYR performed a good capacity of SC service.

4.3. Effect of the restoration project

Anthropogenic activities can exert important effects on ecosystems (Vitousek et al., 1997). In the midst of year 2000 and 2010, we assumed that the K, LS, and P factors in the framework of USLE were stationary, and the remaining two factors of R and C were dynamic. Though the mean annual R factor value in 2010 (886.1 MJ mm/hm^2·h·a) was greater than that value of 2000 (594.1 MJ mm/hm^2·h·a) in AUMYR, the actual soil erosion rate in 2010 (6.48 t/hm^2·a) was still less than that value of year 2000 (7.47 t/hm^2·a). This ascribed to the variation of C factor value. In recent years, the vegetation cover has obviously increased after the initiating of the Grain for Green Project (Fu et al., 2011; Wang et al., 2015; Chen et al., 2015) and this resulted in the descending of the C factor value from year 2000 to year 2010. Vegetation plays an important role in controlling soil erosion. The mean capacity of SC service was 142.2 t/hm^2 in 2000 and 200.8 t/hm^2 in 2010. The improvement of vegetation cover in AUMYR led to the enhancement of ecosystem SC capacity. The decrease of sediment discharge in the middle Yellow River (Jiao et al., 2014; Shi and Wang, 2015) partly reflected the increase of SC capacity of ecosystem.

The modeling result in this study is difficult to validate with field measurement data. There is no strong comparability in different referencing research on SC services for different modeling method, indices for selection, etc. Therefore, verification of the estimated results should be strengthening.

5. Conclusions

Soil erosion and soil conservation (SC) capacity were simulated with the USLE model through parameter localization in 2000 and 2010 in the area of the Upper and Middle of the Yellow River (AUMYR), China, one of the five key development areas within a recent future period. The spatial distribution characteristics and influences of SC service were analyzed. The results showed that ecosystems can retain a large number of soil erosion, with a total of 7.22 billion t/a in 2000 and 10.19 billion t/a in 2010 of soil being retained in AUMYR. SC service displayed unevenly with south-eastern of AUMYR performing much better than the north-west. Great SC capacity primarily was located in the mountainous areas. Specifically, ecosystems located in the cities of Baoji, Tongchuan, and Yan'an had higher SC capacity because they have relatively high precipitation and good vegetation coverage. In different ecosystems, woodland ecosystems had the highest SC service and the SC capacity of ecosystems increased with the increasing of slope gradient. Changes of SC rate in different units were relatively small and ca. 90% of potentially eroded soil was conserved in the whole AUMYR. Topography was the dominant controlling factor for the spatial characteristics of SC service in AUMYR. Benefited from improved vegetation cover, the capacity of SC service in AUMYR was enhanced significantly. In fact, great efforts should be implemented with ground data to strengthen the result.

Declarations

Author contribution statement

Zhu Mingyong, He Wenming, He Hongming: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Zhang Quanfa: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Xiong Yongzhu, Tan Shuduan: Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Funding statement

This work was supported by the research grants kindly provided by Open Funding Project of the Key Laboratory of Aquatic Botany and Watershed Ecology, Chinese Academy of Sciences.

Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

Acknowledgements

The authors are grateful to the editors of the journal and the three anonymous reviewers for their valuable comments and suggestions.

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