Spatial patterns and impacts of soil conservation service in China

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ABSTRACT

We quantified the soil conservation service of ecosystems in China on a GIS platform using the Universal Soil Loss Equation (USLE) and revealed spatial patterns and impacts of this service. The results showed that the total amount and mean capacity of soil conservation service in China were 214.64 billion $t\ a^{-1}$ and 224.42 $t\ ha^{-1}\ a^{-1}$, respectively. South-east China generally displayed a much higher capacity than the north-west, and ecosystems with a capacity of $>1000\ t\ ha^{-1}\ a^{-1}$ were primarily located in mountain areas, including the Tsinling, Nanling, and Wuyi Mountains. Through comparisons, ecosystems located in the provinces of Fujian, Guangxi, Zhejiang, those in the basins of south-eastern rivers, the Pearl River, and the Yangtze River, and those at elevations of 200–1000 m all performed much better than others, from the erosion control perspective. As for the impacts, the spatial characteristics of soil conservation service in China were primarily controlled by climate and terrain at the national scale. In addition, population growth might not affect the soil conservation service directly, whereas land reclamation could impair this service and subsequently exacerbate soil erosion. Finally, the results of this study could contribute to soil erosion control and ecosystem protection in China.

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1. Introduction

Ecosystem services are the foundation on which human survival and development depend (Ouyang and Zheng, 2009). Soil conservation (SC), which is a fundamental regulating service, is defined as the reduction of soil erosion (we focus on water erosion in this study) by ecosystems through their structures and processes (Ausseil et al., 2013). It is reported that ~60% (15 out of 24) of the ecosystem services evaluated worldwide are being degraded, including SC (MEA, 2005), which will undoubtedly exacerbate the serious soil erosion problems.

In China, the degradation of SC has resulted in soil erosion becoming one of the most prominent national ecological problems. Nearly one-third of China's land area is suffering from soil erosion, resulting in an economic loss equivalent to ~3.5% of total GDP (Chen, 2012). In addition, soil erosion can lead to land degradation and lake/reservoir siltation (Canton et al., 2011), thus threaten ecological security, food security, and flood protection. Accordingly, assessment and enhancement of SC service in China will be critical to controlling soil erosion and ensuring ecological security.

The Universal Soil Loss Equation (USLE) is an empirical model established by the U.S. Department of Agriculture for predicting soil erosion rates in the USA (Wischmeier and Smith, 1978). It has been

widely applied around the world owing to its simple form and ease of use. Especially, when combined with GIS, it is endowed with the capability of spatial analysis and large-scale applicability (Van der Knijff et al., 2000; Pham et al., 2001; Yang et al., 2003; Zhao et al., 2009). Besides its use in soil erosion research, the USLE has been successfully embedded in ecosystem service models, such as InVEST (Tallis et al., 2010), for evaluation of SC service (Nelson et al., 2009; Rife, 2010; Bai et al., 2011; Ren et al., 2011). Parameter localization, which determines the performance of empirical models to some extent, is considered to be a premise though. In this study, we quantified the SC service of ecosystems in China at the national scale on a GIS platform using the USLE model and new achievements in parameters to reveal the spatial patterns and impacts of this service. The results of this study will contribute to soil erosion control and ecosystem protection in China.

2. Materials and methods

2.1. Model description

The SC of ecosystems can be described as soil erosion prevention (Ausseil et al., 2013), which is the difference between potential and actual soil erosion, with the USLE model being used. The flow chart for SC assessment and analyses is shown in Fig. 1.

The models are presented as follows:

$$\text{Potential soil erosion} : SE_p = R \times K \times LS \quad (1)$$

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Fig. 1. Flowchart for soil conservation assessment and analyses. *R*, *K*, *LS*, *C*, and *SC* represent the rainfall erosivity factor, soil erodibility factor, topographic factor, vegetation cover factor, and soil conservation capacity, respectively.

$$\text{Actual soil erosion : } SE_a = R \times K \times LS \times C \quad (2)$$

$$\text{Soil conservation : } SC = R \times K \times LS \times (1 - C) \quad (3)$$

where, SE_p and SE_a denote the potential and actual soil erosion rates; SC is the soil conservation capacity; R is the rainfall erosivity factor; K is the soil erodibility factor; LS is the topographic factor; and C is the vegetation cover factor, which refers to the protection of soil by ecosystems in this study.

2.2. Parameters

2.2.1. Rainfall erosivity factor (*R*)

Rainfall erosivity, which describes the potential of rainstorms to cause soil erosion, is determined by rainfall kinetic energy and rainfall intensity (Wischmeier and Smith, 1978; Zhang et al., 2002). We adopted mean annual rainfall erosivity at 603 weather stations nationwide from 1981 to 2010 (Table 1), which was calculated using the Daily Rainfall Erosivity model (SCO, 2010), the latest progress in rainfall erosivity research in China. Interpolation using the Kriging method was employed then to obtain a raster layer of the R factor (spatial resolution of 90 m).

The Daily Rainfall Erosivity model (SCO, 2010) can be described as:

$$\bar{R} = \sum_{k=1}^{24} \bar{R}_k \quad (4)$$

$$\bar{R}_k = \frac{1}{N} \sum_{i=1}^N \left(\alpha \sum_{j=1}^m P_{dij}^\beta \right) \quad (5)$$

$$\alpha = 21.239\beta^{-7.3967} \quad (6)$$

$$\beta = 0.6243 + \frac{27.346}{\bar{P}_d} \quad (7)$$

$$\bar{P}_d = \frac{1}{n} \sum_{l=1}^n P_{dl} \quad (8)$$

where, $\bar{R}$ is the mean annual rainfall erosivity ($\text{MJ mm ha}^{-1} \text{ h}^{-1} \text{ a}^{-1}$); $\bar{R}_k$ 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; α and β account for regression coefficients; $\bar{P}_d$ 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 ($k = 1, 2, \dots, 24$); i represents the order of years in the study period ($i = 1, 2, \dots, N$); j represents the order of days in the k -th half month of the i -th year ($j = 1, 2, \dots, m$); and l represents the order of days in the entire study period ($l = 1, 2, \dots, n$). Note that only days with precipitation greater than or equal to 12 mm are included.

2.2.2. 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 (Zhang et al., 2007, 2008). In this study, we used the formula in Erosion/Productivity Impact Calculator (EPIC) for calculation and the research conducted by Zhang et al. (2008) for revision, making it applicable to the properties of soils in China.

$$K_{\text{EPIC}} = \{0.2 + 0.3 \exp[-0.0256m_{\text{sand}}(1 - m_{\text{silt}}/100)]\} \times \left[m_{\text{silt}} / (m_{\text{clay}} + m_{\text{silt}}) \right]^{0.3} \times \{1 - 0.25\text{orgC} / [\text{orgC} + \exp(3.72 - 2.95\text{orgC})]\} \times \left\{ 1 - 0.7(1 - m_{\text{sand}}/100) / \left\{ (1 - m_{\text{sand}}/100) + \exp[-5.51 + 22.9(1 - m_{\text{sand}}/100)] \right\} \right\} \quad (9)$$

$$K = (-0.01383 + 0.51575K_{\text{EPIC}}) \times 0.1317 \quad (10)$$

where, K_{EPIC} and K are the soil erodibility factor ($\text{t ha h ha}^{-1} \text{ MJ}^{-1} \text{ mm}^{-1}$) before and after revision, respectively; and m_{sand} , m_{silt} , m_{clay} , and orgC are the mass percentages of sand (0.02–2 mm), silt (0.002–0.02 mm), clay (<0.002 mm), and organic carbon, respectively. The soil properties were derived for each 90×90 m cell from the 1:1,000,000 soil map (Table 1).

2.2.3. Topographic factor (*LS*)

The topographic factor reflects the impact of slope length and steepness on soil erosion (Wischmeier and Smith, 1978). Although the exact relationship remains uncertain, we assumed that a greater flow accumulation and a faster runoff velocity were, respectively, associated with a longer slope length and steeper slope, and that the erosion rate would stop increasing when the slope reached a certain threshold (Wang and Jiao, 1996). Accordingly, we made some revisions in the calculation based on previous studies (McCool et al., 1993; Liu et al., 1994; Van Remortel et al., 2001), with gentle slopes and steep slopes being differentiated.

$$L = (\lambda/22.13)^m \quad (11)$$

Table 1
Principal data sources.

Data name	Data resolution	Data source
SRTM digital elevation model	90 m	International scientific data service platform
Soil map	1:1,000,000	Chinese Academy of Sciences
Ecosystem map	90 m	Chinese Academy of Sciences
NOAA-AVHRR-NDVI	1 km	Thematic database for human–earth system
Mean annual rainfall erosivity	603 points	Beijing Normal University
Population	Counties	Statistical Yearbook 2009
Cropland percentage	Counties	Statistical Yearbook 2009

$$m = \beta / (1 + \beta) \quad (12)$$

$$\beta = (\sin \theta / 0.089) / [3.0 \times (\sin \theta)^{0.8} + 0.56] \quad (13)$$

$$S = \begin{cases} 10.8 \sin \theta + 0.03 & \theta < 5.14^\circ \\ 16.8 \sin \theta - 0.5 & 5.14^\circ \leq \theta < 10.20^\circ \\ 21.91 \sin \theta - 0.96 & 10.20^\circ \leq \theta < 28.81^\circ \\ 9.5988 & \theta > 28.81^\circ \end{cases} \quad (14)$$

where L is the slope length factor; S is the slope steepness factor; m is the slope length index; θ is slope gradient ($^\circ$); and λ is slope length (m). We computed the morphometric parameters from the 90-m SRTM digital elevation model (DEM; Table 1).

2.2.4. Vegetation cover factor (C)

Vegetation plays a significant part in controlling soil erosion (Collins et al., 2004; Zhou et al., 2006). The vegetation cover factor is critical to soil and water conservation, owing to its high sensitivity to natural and anthropogenic activities (Wang et al., 2001; Ma et al., 2012). Here, the value of the C factor was primarily obtained by referring to previous studies, with a smaller value linking to better controlling effect. For forests, shrubs, and grasslands, a look-up table (Table 2) that considered both the type and coverage of ecosystems was employed (Wei et al., 2002). For farmlands (except paddy lands), the model established by Liu et al. (1999) was applied. While for wetlands (including paddy lands, a type of farmland), cities, and bare lands (e.g., deserts, lichens), values of 0, 0.01, and 0.7 were assigned, respectively, based on the parameters used in N-SPECT (Carter and Eslinger, 2004).

The C factor model for farmlands (Liu et al., 1999) can be described as:

$$C = 0.221 - 0.595 \log c \quad (15)$$

where, C is the vegetation cover factor of farmland; and c is the vegetation fraction in decimal format, which was estimated from NDVI (Table 1) using the dimidiate pixel model (Li et al., 2004).

2.3. Data analyses

2.3.1. Spatial analyses

Spatial Analyst tools in ArcGIS were employed to reveal the spatial distribution of SC service, with different provinces, primary river basins, and altitudes considered. The mean capacities and total amounts of SC service in corresponding units were consequently calculated.

2.3.2. Correlation and regression

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 (SE_p ; Eq. (1)). We also employed a stepwise regression between SC and impacts (climate, soil, terrain, and vegetation, represented by the R , K , LS , and C factors, respectively) to reveal their relative contribution in influencing the spatial characteristics of SC service.

To discuss the influence of human activities on SC service, we adopted a partial correlation between SC and anthropogenic factors (population growth and land reclamation, represented by population

density (PD) and areal cropland percentage (CP), respectively), since PD and CP were significantly correlated ($r = 0.437$, $n = 2139$, $p < 0.001$). All statistical analyses mentioned in this section were performed at the county level.

2.4. Data sources and processing

The data which were used in our study could be simply grouped into spatial data and statistics. Some details concerning the data are listed in Table 1. In addition, ecosystems were classified into seven categories in this study, including forests, shrubs, grasslands, farmlands, wetlands, cities and bare lands. The calculations and analyses were implemented using ArcGIS 9.3, SPSS 17.0, and SigmaPlot 11.0.

3. Results

3.1. Model validation

To assure the model's regional applicability, we validated the USLE model with soil erosion rates estimated from observed data for seven major river basins in China (MWR et al., 2010). The simulations (USLE) of soil erosion rates agreed well with the corresponding estimates ($r = 0.821$, $n = 7$, $p < 0.05$; Fig. 2). Therefore, we could confirm that USLE and its parameters used here were able to simulate general soil erosion conditions in China. Indirectly, the model of the SC service could also be considered reasonable.

3.2. Spatial characteristics of SC

The potential and actual annual soil erosion was calculated to be 229.75 billion t and 15.11 billion t, respectively. Thus, the total amount of soil retained was 214.64 billion $t a^{-1}$, with a mean capacity of 224.42 $t ha^{-1} a^{-1}$. The SC service displayed great heterogeneity in terms of its spatial distribution, with south-east China generally performing much better than the north-west (Fig. 3). Ecosystems with a great capacity ($>1000 t ha^{-1} a^{-1}$) were primarily located in the Tsinling Mountains, the hills surrounding the Sichuan Basin, the Nanling Mountains, the Wuyi Mountains, and the mountain areas of southern Anhui Province and central Hainan Province.

3.2.1. Regional distributions of SC

Comparisons among provinces (Fig. 4A) indicated that Fujian Province had the highest SC capacity, followed by Guangxi, Zhejiang, Chongqing, and Guangdong. With regard to the total amount, ecosystems in

Fig. 2. Validation of the USLE model. The simulations (USLE) and observations (MWR et al., 2010) of mean annual soil erosion rates correspond to specific parts of river basins, including those of the Songhua, Haihe, Liaohe, Pearl, Huaihe, Yangtze, and Yellow.

Table 2
C factor values for various ecosystems (after Wei et al., 2002).

Ecosystem types	Vegetation fraction (%)					
	<10	10–30	30–50	50–70	70–90	>90
Forests	0.10	0.08	0.06	0.02	0.004	0.001
Shrubs	0.40	0.22	0.14	0.085	0.040	0.011
Grasslands	0.45	0.24	0.15	0.09	0.043	0.011

Fig. 3. Spatial pattern of ecosystem soil conservation services in China.

Yunnan, Guangxi, and Sichuan contributed most, accounting for 11.51%, 10.89%, and 10.23%, respectively, of the total. The accumulative proportion would be greater than four-fifths when the provinces of Hunan, Fujian, Guizhou, Shannxi, Jiangxi, Hubei, Zhejiang, and Chongqing were added, while the sum of area ratio was only about one-fourth.

Comparisons among primary river basins (Fig. 4B) showed that the basins of the south-eastern rivers, the Pearl River Basin, and the Yangtze River Basin had the highest SC capacities, and the Yangtze River Basin had the largest amount, accounting for 42.24% of the total. What followed was the Pearl River Basin, accounting for 22.70% of the total.

Comparisons among altitudes (Fig. 4C) showed that ecosystems with an elevation of 200–500 m displayed the highest SC capacities, followed by those with an elevation of 500–1000 m. With regard to quantities, ecosystems located at elevations of 200–500, 500–1000, and 1000–2000 m retained much more soil than others, with those located at 500–1000 m preserving most (~30% of the total).

3.2.2. Relationship between SC and soil erosion risk

The SC capacity displayed a significant positive correlation ($r = 0.998$, $n = 2273$, $p < 0.001$; Fig. 5) with potential soil erosion rate, which was determined by climate, soil, and terrain. Where the risk of soil erosion is high, the capacity of soil conservation for an ecosystem is considerable.

3.3. Impacts of influencing factors on SC

The spatial characteristics of SC service are formed by the interactions between influencing factors. The stepwise regression indicated that, the R and LS factors could explain most variance in SC, with the variance contribution (VC) reaching 35.7% and 36.3%, respectively. The VC values of the K and C factors were relatively small.

The partial correlation between SC and PD, with CP controlled, was not statistically significant. In contrast, SC was negatively correlated with CP ($r = -0.392$, $n = 2139$, $p < 0.001$), with PD controlled. This

negative correlation could also be observed from the scatter plot based on the unit of county (Fig. 6).

4. Discussion

In the process of parameter localization for the USLE, we analyzed relevant progress in domestic research first, and calculated soil erosion rates as well as SC capacities using recent achievements on the parameters. Through comparison with the estimates of soil erosion rates in river basins, the USLE model and the parameters used herein proved capable of realistically simulating the soil erosion situation in China, thus rendering a satisfactory accuracy to the assessment of SC service. Moreover, a spatial resolution of 90 m was used here, which was the highest up to now for such a large scale, so as to capture the spatial heterogeneity of environmental variables more effectively.

In this study, the actual amount of soil erosion in China was estimated at 15.11 billion $t a^{-1}$, more than the mean measurement of 5 billion t (Peng, 2001). The primary reason for the difference is that the output of the USLE is the amount of soil eroded or moved (Yang et al., 2003; Rife, 2010), while the measurement usually refers to the sediment yield at river outlets. They are not equivalent concepts and therefore not directly comparable. The total amount of SC, which describes the reduction in soil erosion by ecosystems, was estimated at 214.64 billion $t a^{-1}$, with a mean capacity of 224.42 $t ha^{-1} a^{-1}$, well matching the SC capacity of forests and grasslands (118.61–445.92 $t ha^{-1} a^{-1}$) that was determined through surveys and syntheses (Ouyang et al., 1999).

The ecosystems' SC service in China was spatially unevenly distributed, due to the vast territory and enormous differences in environmental conditions. Ecosystems located in the provinces of Fujian, Guangxi, Zhejiang, in the basins of south-eastern rivers, the Pearl River, the Yangtze River, and at elevations of 200–1000 m all demonstrated excellent soil erosion control, thus deserving careful protection in the future. Additionally, based on the positive correlation between SC service and soil erosion risk, greater importance should be given to higher erosion

Fig. 4. Spatial distribution of soil conservation service according to (A) provinces, (B) river basins, and (C) altitudes. (A) BJ – Beijing; TJ – Tianjin; HE – Hebei; SX – Shanxi; NM – Neimeng; LN – Liaoning; JL – Jilin; HL – Heilongjiang; SH – Shanghai; JS – Jiangsu; ZJ – Zhejiang; AH – Anhui; FJ – Fujian; JX – Jiangxi; SD – Shandong; HA – Henan; HB – Hubei; HN – Hunan; GD – Guangdong; GX – Guangxi; HI – Hainan; CQ – Chongqing; SC – Sichuan; GZ – Guizhou; YN – Yunnan; XZ – Xizang; SN – Shanxi; GS – Gansu; QH – Qinghai; NX – Ningxia; XJ – Xinjiang. (B) A – Songhua River Basin; B – Liaohe River Basin; C – Haihe River Basin; D – Yellow River Basin; E – Huaihe River Basin; F – Yangtze River Basin; G – basins of south-eastern rivers; H – Pearl River Basin; J – basins of south-western rivers; K – basins of north-western rivers.

risk areas (Rahman et al., 2009), such as the Loess Plateau and south-eastern China, since the state of ecosystems in these areas could be fairly critical to the actual situation of soil erosion.

Overall, south-eastern China displayed a much higher SC capacity than the north-west (Sheng et al., 2010), quite similar to the spatial pattern of precipitation (Wang and Ding, 2008). Ecosystems with a great SC capacity ($>1000 \text{ t ha}^{-1} \text{a}^{-1}$) were primarily located in mountain areas, such as the Tsinling, Nanling, and Wuyi Mountains, implying a potential influence of topography. Stepwise regression further demonstrated that the spatial patterns of SC service in China were primarily controlled by climate and terrain, while the effects of soil and vegetation were relatively small at the national scale. The probable reason was that the natural patterns of soil and vegetation greatly depended on the climate and terrain at a large scale, and the multicollinearity among factors weakened the contribution of soil and vegetation. At small scales,

when climate and terrain were relatively uniform, soil and vegetation probably became dominant factors, just like the situation in the Zhangjiajie National Forest Park, China (Zhao et al., 2009).

Anthropogenic activities, such as population growth and land reclamation, are the main drivers of change in ecosystems and their services (Zheng et al., 2003; Ouyang and Zheng, 2009; Su et al., 2012). The population exerts significant pressure on ecosystems if its size is large and density is high, and agricultural lands have been regarded as major sources of sediment (Pimentel et al., 1995; Lin et al., 2008). A negative partial correlation was found between SC and CP, while no significant correlation was found between SC and PD. These findings suggest that population growth could not directly influence the SC service, but land reclamation could impair it and intensify soil erosion through changing ecosystem structures and processes (Zheng et al., 2003; Ouyang and Zheng, 2009). A slowdown or reversal of land reclamation would be

Fig. 5. Relationship between soil conservation service and soil erosion risk. Each dot represents a county. The line represents the fitted curve.

very helpful in soil erosion control in China (Feng et al., 2010; Su and Fu, 2013), which is the principal motivation for the Grain-to-Green and similar projects (Lü et al., 2012).

5. Conclusions

Through parameter localization and using high resolution data, a satisfactory overview was obtained in soil erosion and soil conservation in China. The spatial patterns and impacts of soil conservation service, which were significant in soil and water conservation planning, were also discussed using spatial analyses and statistical analyses. The results suggest that:

- 1) Ecosystems can reduce a huge amount of soil erosion, with a total of 214.64 billion t of soil being conserved annually in China.
- 2) Soil conservation service displays great spatial heterogeneity, with south-eastern China performing much better than the north-west, and regions with a great capacity primarily located in mountain areas. Specifically, ecosystems located in the provinces of Fujian, Guangxi, Zhejiang, those in the basins of south-eastern rivers, the Pearl River, the Yangtze River, and those at elevations of 200–1000 m demonstrate excellent soil erosion control, thus deserving careful protection in the future.

Fig. 6. Relationship between soil conservation service and cropland percentage. Each dot represents a county. The line represents the fitted curve.

- 3) The spatial characteristics of soil conservation service in China are primarily dominated by climate and terrain at the national scale.
- 4) Land reclamation can impair soil conservation service and exacerbate soil erosion subsequently.

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