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Quantifying the efficiency of soil conservation and optimized strategies: A case-study in a hotspot of afforestation in the Loess Plateau

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Abstract

Although it is generally believed the Grain for Green programme (GFG) implemented in China has attenuated soil erosion, the extent to which it is effective still needs verification. Taking Yan'an in the Loess Plateau as the study area, we analysed both total effect and efficiency differences during GFG implementation. Results showed that, while soil erosion on average decreased from 4,884.49 to 4,087.57 t km^{-2} yr^{-1}, counties with higher GFG implementation intensity achieved a lower soil conservation effect. For example, Wuqi ranks third in the GFG implementation intensity among all counties in Yan'an, but its actual soil erosion reduction is the lowest, only 54.1% of Yan'an's average level. To analyse the reason for the efficiency difference, the concept of soil conservation potential was proposed. It is concluded that the soil conservation effect is controlled by the soil conservation potential. Ideally, regions with high soil conservation potential should get priority in the GFG application, yet there is a significant spatial mismatch between the GFG implementation intensity and the soil conservation potential because the correlation coefficient is only −0.05, which weakened the soil control effect. A dynamic implementation mechanism was put forward for the formulation and optimization of ecological programmes and projects in future: first, using the soil conservation potential to determine the implementation intensity in each region; second, adjusting the intensity to the changes of the soil conservation potential in the following implementation; third, repeating above steps to ensure high efficiency of soil erosion control, and achieving the sustainability and effectiveness of the ecological projects.

KEYWORDS

Grain for Green programme, optimizing strategy, soil conservation efficiency, soil conservation potential, spatial mismatch

1 | INTRODUCTION

To curb degradation and restore the deteriorating environment, the Chinese Government has introduced a series of ecological programmes and projects since the end of the 20th century (Yin, Yin, & Li, 2010). The Grain for Green programme (GFG) is one of the most famous of these ecological initiatives. The GFG aimed to restore and improve the environment at the expense of reducing the cultivation land used by farmers. Studies have shown that the implementation of the GFG has promoted ecosystem services in relevant areas, such as an increase in vegetation coverage (Xiao, 2014), a decrease in soil erosion (Lü et al., 2012), a raised carbon sink (Wang et al., 2018), and enhanced per-unit yield of cultivated land (Zhang et al., 2019). In the Loess Plateau, the most important ecosystem function the GFG aimed at was control soil erosion, which was the most prominent ecological problem in the area (Qiu, Fu, & Wang, 2002; Wang, Ouyang, Xiao, Miao, & Fu, 2001; Zhang, Zhang, Yang, & Zhu, 2019). From 1955 to 1989, about 56.6% of the Loess Plateau had an average annual soil loss of 2,500 t km^{-2}, which was considered to be a moderate erosion level (Wang & Jiao, 2002). Serious soil erosion not only endangered the socioeconomic development and environmental security within the region but also caused a significant negative impact on the nearby areas (Chen, Zhu, & Mao, 2008). Since the implementation of the GFG in the Loess Plateau, the soil erosion has been controlled to a certain extent, through the adjustment and optimization of the land use structure, the improvement of vegetation cover, and engineering measures (Deng, Shangguan, & Li, 2012; Wang et al., 2016).

In recent years, researchers have carried out a series of studies on the measurement of soil conservation brought about by the GFG from different perspectives, mainly including empirical models and field observation. An empirical model was often used to analyse the soil erosion at different stages and evaluate the soil conservation effect (SCE), for example, the USLE model (Fu et al., 2011), the SWAT model (Yang & Lu, 2018), WATEM/SEDEM (Li et al., 2019), and so on. Some researchers simulated the soil erosion in different situations, thus expanding the application of the empirical models (Han, Ren, Zhang, & Li, 2016; Hessel, Messing, Chen, Ritsema, & Stolte, 2003; Zhou, Shangguan, & Zhao, 2006). Field observation included the use of data on river run-off, sediment content, and sediment transport obtained from published data or experiments seeking to analyse the impact of GFG on soil erosion in specific areas, especially at the river basin scale, and these were all used to make suggestions for feasible measures (Deng et al., 2019; Gao, Fu, Zhang, Ma, & Sivapalan, 2018; Yang et al., 2018). In addition, although some studies used empirical models to calculate the soil erosion, they also verified the empirical models through experimental observations, thus ensuring the reliability of the empirical model results (Jiang, Zhang, Wang, Feng, & Labzovskii, 2019; Jiang, Zhang, Zhang, & Wang, 2019; Sun, Shao, Liu, & Zhai, 2014).

Various improvements, especially soil conservation benefits resulting from the GFG in the Loess Plateau, have been extensively evaluated in previous studies (Jiang, Zhang, Wang, et al., 2019; Wang et al., 2016; Yang, Wang, & Xu, 2018). However, there are still some aspects that can be improved. First, past studies focused on overall effect evaluation of the GFG on soil erosion control, while the consideration of local effects and their differences in spatial distribution has been inadequate. Since the GFG is a policy-oriented programme, there may be differences in implementation in various places (Bullock & King, 2011; Yin & Zhao, 2012); in addition, the ecology, environment, and resource endowment may also vary locally and cause differences in SCE (Jiang, Zhang, Wang, et al., 2019; Jiang, Zhang, Zhang, & Wang, 2019). Without considering the spatial differences of GFG implementation, ecology, environment, and resource endowment, an unbalanced view may be obtained when making an SCE evaluation. Second, most previous studies analysed the achievement of the GFG in improving soil erosion control over time (Wen, 2020; Wu, Wang, Fu, Feng, & Chen, 2019; Xin, Ran, & Lu, 2012); however, many useful aspects are still unknown. In other words, the potential for soil conservation, which can help to measure the room for improvement for soil erosion control in different regions (Gao et al., 2016), was not well considered. Third, although there were some studies focusing on the strategic optimization for the GFG programme that will be useful in the future (Feng et al., 2020; Feng, Wei, & Pan, 2020; Geng et al., 2019; Wen, Deng, & Zhang, 2019), few of them saw the improvement as a dynamic process. In fact, the potential for soil conservation not only shows spatial heterogeneity but it can changed with time.

The objectives and novelties of this study are as follows. First, villages and counties were selected as evaluation units, to calculate and compare the SCE in different regions. Second, the concept of soil conservation potential (SCP) was proposed, and the distribution of the SCP was mapped to identify the room for improvement of soil erosion control in various regions. Third, a dynamic implementation mechanism (DIM) was established with the optimized strategy of the GFG determined according to the SCP. This study could provide a reference for the optimization of the GFG strategies, and the promotion of soil conservation efficiency.

2 | STUDY AREA

Yan'an, a city of Shaanxi Province, is located in the centre of the Loess Plateau of China and is adjacent to the Yellow River, with a total area of about 37,000 km^2 (Figure 1). In 2018, the resident population of Yan'an was about 2.5294 million, and the urbanization rate reached 62.31%. The terrain of Yan'an is high in the northwest and low in the southeast, with an average elevation of about 1,200 m. Yan'an has a typical temperate continental monsoon climate with concentrated

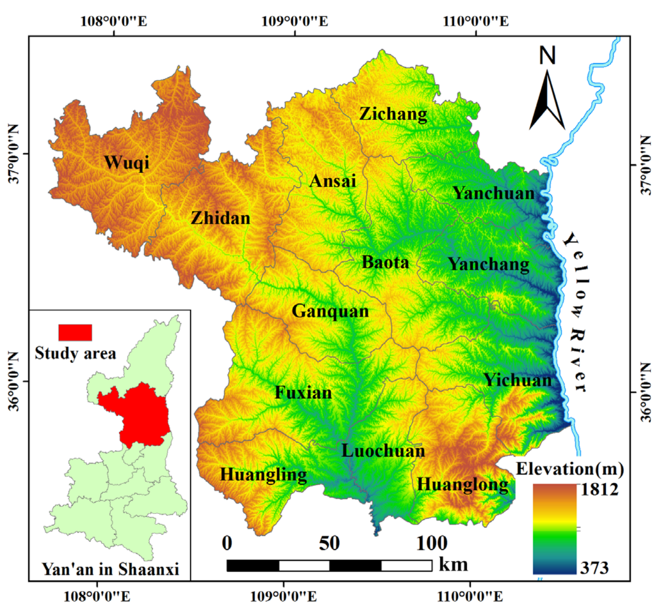

FIGURE 1 Basic situation of the study area [Colour figure can be viewed at wileyonlinelibrary.com]

precipitation. Geological and climatic conditions are important factors that make the region prone to soil erosion. Yan'an is one of the Chinese cities/city regions with the most severe soil erosion and was also one of the earliest to adopt GFG pilot projects. Since the start of the GFG, it has been a hotspot of GFG-related research (Fu et al., 2009; Wang, Wang, Xie, & Luo, 2019). In recent years, due to the implementation of the GFG, the vegetation coverage in Yan'an has significantly improved, and the soil erosion has also been significantly controlled (http://www.yanan.gov.cn/xwzx/bdyw/394103.htm).

3 | MATERIALS AND METHODS

3.1 | Data sources and preprocessing

The meteorological data were downloaded from the Climate Forecast System Reanalysis (https://globalweather.tamu.edu), which provides daily meteorological indicators for each grid formed by latitude and longitude lines. The data were used to calculate the average annual precipitation and the average precipitation each month.

The soil data were obtained from the Harmonized World Soil Database (http://webarchive.iiasa.ac.at/Research/LUC/), which was in the format of raster data with an original resolution of approximately 30 arc sec.

ASTER GDEM Version 2, provided online by the Chinese Academy of Sciences (http://www.gscloud.cn), was used to establish the digital elevation model (DEM) of the study area, and the original spatial resolution was 30 m. The DEM was then used to calculate the maps of the slope steepness and slope length using ARCGIS 10.2 and LS-TOOL (Zhang et al., 2013), respectively.

The land use data were derived from the human–computer interaction interpretation of the remote sensing images. According to the research needs, LANDSAT 5 TM images in 2000 and LANDSAT 8 OLI_TIRS images in 2015 were selected as the base maps for interpretation. Then, the land use maps for 2000 and 2015 were obtained through image interpretation corresponding to the year, and the spatial database update from the land use map in 2010, which was obtained by Zhang et al. (2020). The source of remote sensing images data was the same as that of the topography data, and the original spatial resolution was also 30 m. The GFG implementation intensity was defined as the area ratio between the cultivated land converted to forest or grassland, and the original cultivated land, which should be a dimensionless value ranging from 0 to 1 (Zhang, Jia, et al., 2019). The area for each land use transfer type can be obtained through the spatial overlay analysis using the land use maps in 2000 and 2015 mentioned above as input files.

With respect to vegetation coverage data, MOD13Q1 Version 6 (Didan, 2015) offers the advantages of calculating with both temporal resolution (16 days) and spatial resolution (250 m), and was used in this study. Although vegetation index products with higher spatial resolution can be calculated based on the LANDSAT data, its temporal resolution is poor and it is very vulnerable to climatic conditions. In fact, vegetation index produced with MODIS have even been applied to some small-scale regions of research (Lu & Fan, 2016; Veeck, Li, Yu, & Emerson, 2015). Both Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI) are included in MOD13Q1, and the latter performs better when the vegetation is saturated (Gu, Wylie, Howard, Phuyal, & Ji, 2013; Li, Li, Wei, Xu, & Wang, 2010). For this reason, EVI data from 2000 to 2016 were selected in this study to calculate the cover and management factor. The average EVI from the 97th to 289th days of each year was taken as the year's EVI during the plant growth season (see Xu, Zhang, Zhang, Yao, & Zhang, 2020).

The population data were collected from the Statistical Yearbook of Yan'an (http://data.cnki.net), and the resident population of each county in 2015 was selected to predict the basic cultivated land requirement.

Finally, all data were presented in grids with a resolution of 90 m × 90 m, using the World Geodetic System 1984 (WGS-84) projected coordinate system, with 111°E as the central meridian and Universal Transverse Mercator (UTM) as the projection. The regions with a slope below 6° were ignored because the GFG was rarely carried out in such areas (Zhang et al., 2019).

3.2 | Study methods

3.2.1 | Revised universal soil loss equation

The revised universal soil loss equation (RUSLE) is an empirical model for estimating soil erosion, which has been widely used in current situation evaluation, risk estimation, simulation, and prediction (Panagos et al., 2015; Prasannakumar, Vijith, Abinod, & Geetha, 2012; Zare, Panagopoulos, & Loures, 2017). The specific form is shown in Equation (1).

$$A = 100 \times R \times K \times L \times S \times C \times P \tag{1}$$

where A is average annual soil loss per unit area (t km^{-2} yr^{-1}), R is rainfall and run-off erosivity factor (MJ mm hm^{-2} h^{-1} yr^{-1}), K is soil erodibility factor (t hm^{2} h hm^{-2} MJ^{-1} mm^{-1}), L is slope length factor (dimensionless), S is slope steepness factor (dimensionless), and C is cover and management factor (dimensionless, 0–1). These factors are calculated from Equations (2) to (6) (Table 1); P is support practice factor (dimensionless, 0–1), which is assigned according to land use type (Li, Wang, & Zhang, 2006; Yang et al., 2003; Table 2).

The calculation method of each factor in the RUSLE has applicability, which has a relationship with the choice of the study area and data acquisition (Guo, Yang, Zhang, Han, & Liu, 2018; Liu, Song, Shi, & Tao, 2016). For example, the formula for the R factor selects the monthly model, because part of the period in the precipitation data is missing. The monthly model can weaken the impact of missing data. The calculation method of the K factor mainly comes from the percentage of each component in the soil, which is closely related to the data information. The slope threshold required to calculate the LS factor was used in the Loess Plateau (Zhang et al., 2013). The formula for the C factor is summarized through experimental data in the Loess Plateau (Liu et al., 1999). In this study, the calculation formulas and

TABLE 1 Calculation methods of rainfall and runoff erosivity factor (*R*), soil erodibility factor (*K*), slope length factor (*L*), slope steepness factor (*S*), and cover and management factor (*C*) in the revised universal soil loss equation (RUSLE)

Factor	Equation	Description	Reference
R	$R = \sum_{i=1}^{12} 1.735 \times 10^{\left[1.5lg\left(P_i^2/P\right) - 0.08188\right]}$ (2)	P_i: mean monthly rainfall (mm) *P*: mean annual rainfall (mm)	Pan and Wen (2014)
K	$K = 0.1317 \times K_1 \times K_2 \times K_3 \times K_4$ (3) and, $K_1 = 0.2 + 0.3exp\{-0.0256SD[1.0 - (SI/100)]\}$ $K_2 = [SI/(CL + SI)]^{0.3}$ $K_3 = 1.0 - \{0.25C/[C + exp(3.72 - 2.95C)]\}$ $K_4 = 1.0 - \{0.7SN/[SN + exp(-5.51 + 22.9SN)]\}$	*SD*: sand fraction (%) *SI*: silt fraction (%) *CL*: clay fraction (%) *C*: organic carbon fraction (%) *SN*: 1−*SD*/100	Yang, Kanae, Oki, Koike, and Musiake (2003)
L&S	$L = (\lambda/22.13)^m$ (4) $S = \begin{cases} 10.8sin\theta + 0.03 & \theta < 9\% \\ 16.8sin\theta - 0.50 & \theta \geq 9\% \end{cases}$ (5) And, $m = \beta/(1 + \beta)$ $\beta = sin\theta/[3(sin\theta)^{0.8} + 0.56]$	λ: horizontal projection slope length *m*: variable slope length exponent β: a factor that varies with slope gradient θ: slope angle (%).	McCool, Foster, Mutchler, and Meyer (1989) Zhang et al. (2013)
C	$C = \begin{cases} 1 & 0 \leq FVC \leq 4.9\% \\ 0.221 - 0.595lgFVC & FVC \geq 4.9\% \end{cases}$ (6) And, $FVC = (EVI - EVI_{min})/(EVI_{max} - EVI_{min})$	*FVC*: the fractional vegetation cover EVI_{min} and EVI_{max}: the minimum and maximum EVI values of the whole study area during the study period	Liu, Liu, and Zheng (1999)

TABLE 2 Support practice factors (*p*) for different land-use types

Land use types	*p* values	Land use types	*p* values
Cultivated land (α < 6°)	.5	Forest	1
Cultivated land (6° ≤ α < 10°)	.6	Grassland	1
Cultivated land (10° ≤ α < 15°)	.7	Water	0
Cultivated land (15° ≤ α < 20°)	.8	Construction land	0
Cultivated land (20° ≤ α < 25°)	.9	Unused land	1
Cultivated land (α ≥ 25°)	1		

related parameters corresponding to various factors were mostly realized in the Loess Plateau (Fu et al., 2011; Gao et al., 2016; Li et al., 2006; Pan & Wen, 2014). Therefore, the calculation of these factors is considered appropriate in the study area.

RUSLE is an empirical model, it is necessary to verify its accuracy (Jetten, Govers, & Hessel, 2003). The ^{137}Cs method was often used to verify the accuracy of RUSLE (Jiang, Zhang, Wang, et al., 2019; Jiang, Zhang, Zhang, & Wang, 2019; Walling, He, & Whelan, 2003), and it was also used in this study. The ^{137}Cs measurements for soil erosion were derived from Wang, Fu, Chen, Lü, and Luo (2009) and Sun et al. (2014). There is a significant relationship ($p < .05$) between the observed of ^{137}Cs and the estimated of RUSLE (Figure 2). The regression coefficient is 1.051 and the coefficient of determination (R^2) is .798. These findings indicated that the results estimated by the RUSLE are relatively accurate.

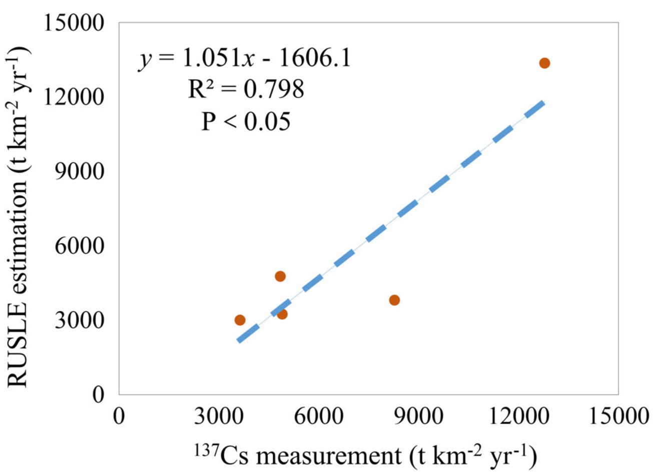

FIGURE 2 Comparison of the soil erosion obtained by ^{137}Cs measurements and the revised universal soil loss equation (RUSLE) estimations [Colour figure can be viewed at wileyonlinelibrary.com]

3.2.2 | The SCP model

In this study, the SCP is defined as the difference between the current value and the theoretical minimum value of average annual soil loss per unit area of a region, reflecting the room for improvement of soil erosion control. According to the RUSLE, in order to control soil erosion, the values of the above factors must be effectively controlled. In fact, precipitation is a long-term and stable feature. Extensive changes in soil properties and topography are difficult in a short period. In this study, only the spatial differences of these factors are considered. Vegetation cover and land use types are directly affected by the implementation of GFG, and they are also important factors affecting soil erosion. Therefore, in the calculation of SCP, the *C* factor and *P* factor will be introduced into the model as the main variables.

The average annual soil loss per unit area when the *C* factor and *P* factor in region *i* reach the ideal state is defined as the theoretical minimum soil erosion level of the region (A_{i0}), and the average annual soil loss per unit area calculated from the actual values of *C* factor and *P* factor in the year *t* is defined as the soil erosion level (A_{it}) of the region in the year *t*. Then the formula of SCP can be defined as Equation (7).

$$SCP_{it} = A_{it} - A_{i0} = R_i \times K_i \times L_i \times S_i \times (C_{it} \times P_{it} - C_{i0} \times P_{i0}) \tag{7}$$

SCP_{it} represents the SCP of region *i* in year *t*. R_i, K_i, L_i, and S_i are, respectively, the rainfall and run-off erosivity factor, soil erodibility factor, slope length factor, and slope steepness factor of region *i*. C_{it} and C_{i0} are, respectively, the values of the cover and management factor of region *i* in year *t* and in the ideal state. Among them, the *EVI* corresponding to C_{i0} comes from the theoretical maximum value of vegetation restoration obtained by constructing similar habitat units based on the spatial sliding window, and references for specific calculation methods (Xu et al., 2020; Zhang, Xu, et al., 2019). P_{it} and P_{i0} are, respectively, the values of the support practice factor of region *i* in year *t* and in the ideal state. The land-use types corresponding to P_{i0} are defined based on the standard of ensuring 1 mu[1] of grain ration field per capita. Based on the resident population data of each county of Yan'an in 2015, the scale of grain ration fields to be reserved in each county was calculated, and the reserved grain ration fields should occupy the lowest part of the originally cultivated land slope. Finally, the remaining cultivated land is supposed to be converted into forest. The layers of each factor are shown in Figure 3.

According to the definition and calculation method of the SCP, it can be considered that if a region owns higher SCP, it indicates that the gap between the current soil erosion level and the theoretical minimum soil erosion level in the region is much bigger, and the GFG implementation intensity in the region should be higher, thereby enhancing the effectiveness of soil erosion control.

3.2.3 | Concept of the SCE

The SCE is defined as the soil loss difference before and after the GFG implementation, which reflects the improvement of soil erosion achieved by the GFG. Similar to the calculation method of SCP, the SCE is also calculated based on the RUSLE under the assumption that the factors of *R*, *K*, *L*, and *S* are only related to the spatial position. Set the average annual soil loss per unit area of region *i* before and after GFG as A_{ib} and A_{ia}, respectively, and then define the SCE formula as Equation (8).

$$SCE_i = A_{ib} - A_{ia} = R_i \times K_i \times L_i \times S_i \times (C_{ib} \times P_{ib} - C_{ia} \times P_{ia}) \tag{8}$$

SCE_i is the SCE of region *i*. R_i, K_i, L_i, and S_i have the same meanings as they are in Equation (7). C_{ib} and P_{ib} are the *C* and *P* factors of the region *i* before the GFG implementation, and C_{ia} and P_{ia} are the *C* and *P* factors of the region *i* after the GFG implementation.

The SCP and the SCE were initially calculated using the grid as the basic unit, while the implementation intensity of GFG was calculated in vector format. In order to make a comparison among them, both the SCP and the SCE were averaged within villages and counties in ARCGIS 10.2. Since the GFG was implemented in 1999, and considering the availability of the data and the project duration, the land use and the EVI data in 2000 and 2015 were used to reflect the corresponding status before and after the GFG implementation.

4 | RESULTS AND ANALYSIS

4.1 | Evaluation of the SCE brought by the implementation of GFG

As shown in Figure 4, in general, the soil erosion in Yan'an decreased from 4,884.49 t km^{-2} yr^{-1} in 2000 to 4,087.57 t km^{-2} yr^{-1} in 2015. This result shows that the effect of GFG on soil conservation is significant. The implementation of GFG has improved the level of vegetation coverage, curbed the increasingly serious soil erosion in Yan'an, and improved the effect of soil conservation.

From the spatial perspective, since the implementation of GFG, the soil erosion in the east, north, and south has declined significantly, while the largest decline occurred in the east. However, in the northwest counties such as Wuqi and Zhidan, the soil erosion decreased less. The regions with soil erosion more than 8,000 t km^{-2} yr^{-1} were almost disappeared in 2015, although they commonly existed in 2000. Besides, regions with the soil erosion between 5,000 and 8,000 t km^{-2} yr^{-1} have been significantly reduced, while the regions with soil erosion between 2,500 and 5,000 t km^{-2} yr^{-1} were increased. The above results show that the soil erosion in Yan'an has been significantly reduced on the whole since the implementation of GFG, and the differences across the study area have been gradually narrowed. In particular, areas with serious soil erosion have achieved remarkable results thanks to the GFG.

4.2 | Spatial distribution relationships among the GFG implementation intensity, the SCE, and the SCP

Figure 5a provides the spatial distribution of the GFG implementation intensity in Yan'an, which shows significant spatial agglomeration. The high-intensity areas of the GFG are concentrated in Wuqi, Baota, Zichang, and Luochuan. The low-intensity areas are mainly distributed in Ansai, Huanglong, Yanchang, and Ganquan. It can be seen that this agglomeration is controlled by the county boundaries. The reason is that the formulation and implementation of related measures for the

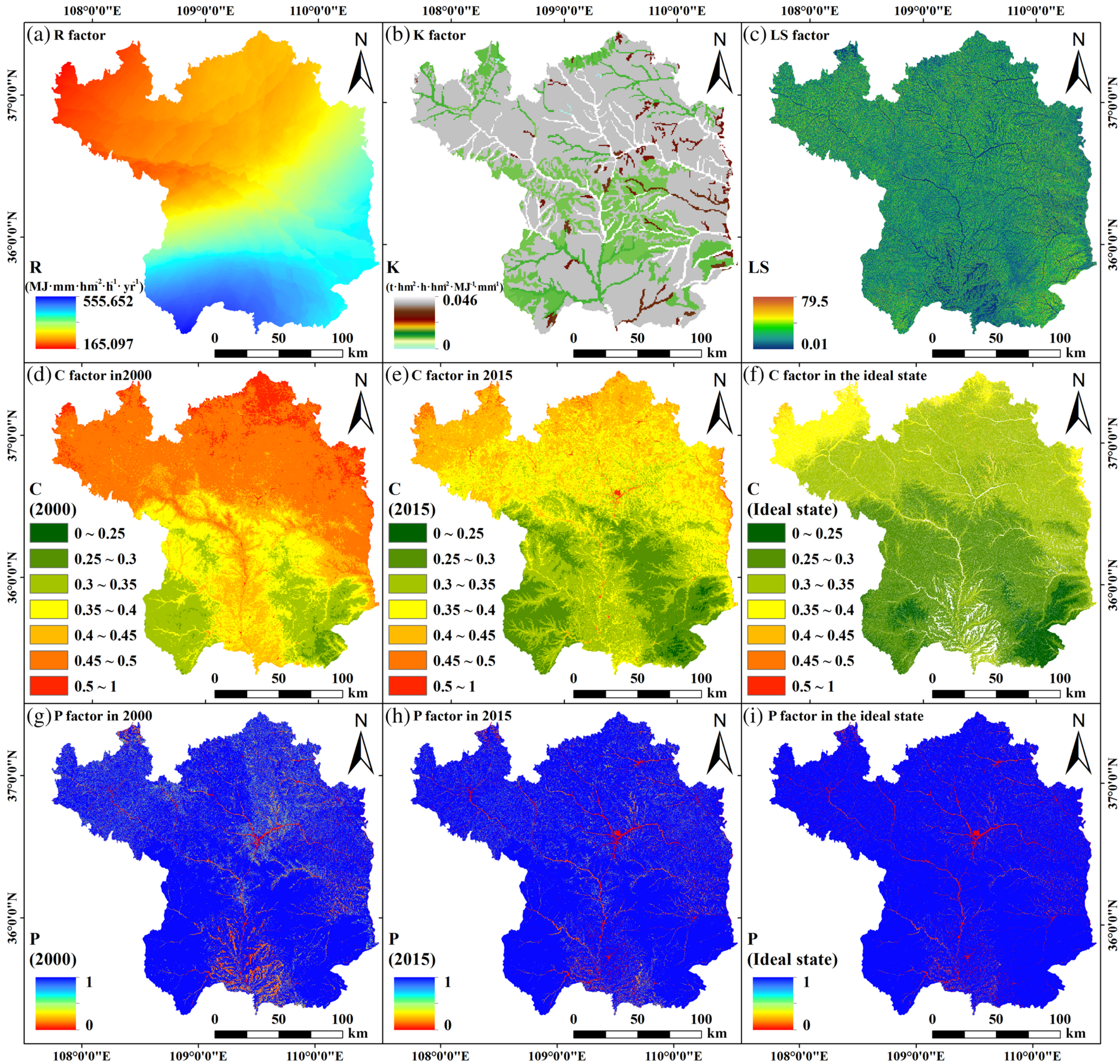

FIGURE 3 Factors of the revised universal soil loss equation (RUSLE) in this study: (a)–(c) rainfall and runoff erosivity factor (*R*), soil erodibility factor (*K*) and slope length and slope steepness factor (*LS*); (d)–(f) cover and management factor (*C*) in 2000, 2005 and the ideal state; (g)–(i) support practice factor (*P*) in 2000, 2005, and the ideal state [Colour figure can be viewed at wileyonlinelibrary.com]

GFG are based on the county level in China. Figure 5b shows the spatial distribution of average SCE in each village during the GFG project (from 2000 to 2015). It can be found that its spatial distribution also shows an obvious agglomeration effect. The areas with obvious high SCE are mainly distributed in the east, south, and Ansai in the north. Although Wuqi, Zhidan, and Baota have also obtained certain achievements, they are not as significant as in other regions.

The above two indicators have their own specific spatial distribution law, and the correlation between them is negative, though the correlation coefficient is only −0.12. By comparing Figure 5a,b, it can be found that Wuqi, Baota, Zichang, and other counties with relatively higher GFG implementation intensity show lower SCE. In Yanchuan, Yanchang, and Yichuan, where the SCE is much higher, the GFG implementation intensity is relatively lower. These results suggest a mismatch between the GFG implementation intensity and the SCE in spatial distribution. That is, the SCE is not necessarily better in areas with relatively higher GFG implementation intensity. Although the main purpose of implementing the GFG in this region is the soil conservation, it did not achieve optimal input allocation.

As mentioned above, the GFG should have been implemented in regions with greater SCP, which is the optimal strategy. Therefore, we compared the SCP in 2000 (Figure 5c) with the GFG

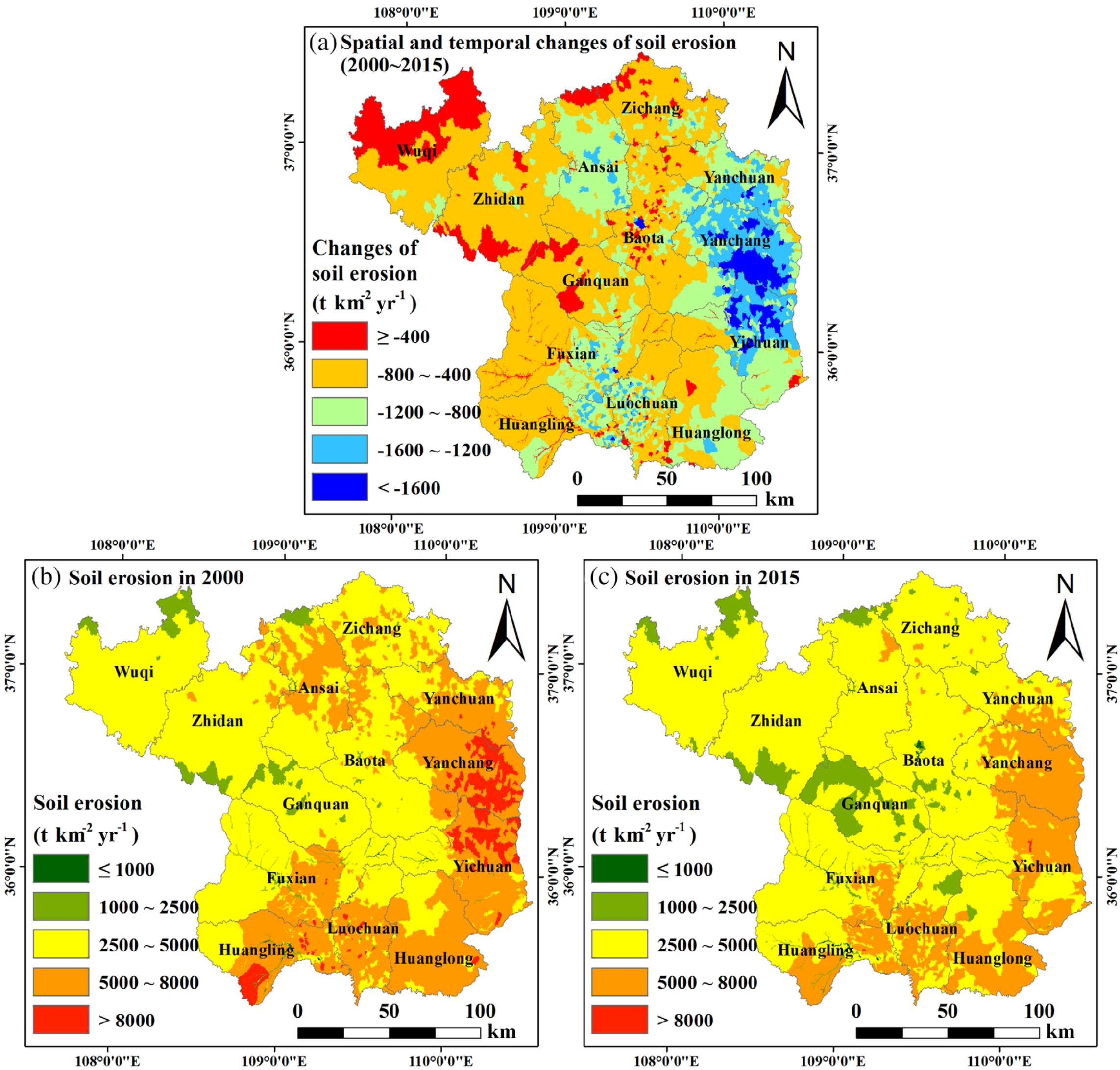

FIGURE 4 (a) Spatial and temporal changes of the soil erosion from 2000 to 2015; (b) Soil erosion in 2000; (c) Soil erosion in 2015 [Colour figure can be viewed at wileyonlinelibrary.com]

implementation intensity (Figure 5a). It is found that the spatial matching degree between the GFG implementation intensity and the SCP in 2000 is low, and the correlation coefficient is only −0.05, which is far from the optimal strategy in theory. Considering that the GFG is mostly organized and implemented in units of counties, all counties in Yan'an were ranked according to the SCP in GFG and the GFG implementation intensity respectively for further comparison. As shown in Table 3, the ranking differences in most counties are large, which further validates the mismatch between the GFG implementation intensity and the SCP. Taking Wuqi as an example, it had the least SCP in 2000, while its GFG implementation intensity rank was the third among all counties in Yan'an. In fact, the real soil erosion reduction in Wuqi was 430.918 t km^{-2} yr^{-1}, which is the lowest among all counties, accounting for only 54.1% of the average level in Yan'an. It indicates that the GFG implementation intensity in Wuqi far exceeded the reasonable range for soil conservation. On the contrary, Yanchuan, Yanchang, and Yichuan in the east part of Yan'an, which had the greatest SCP in 2000, their GFG implementation intensity ranks are low. These results indicate that the SCP was not taken into account in the previous GFG projects, which not only caused a failure in achieving the optimal SCE, but also caused a waste of resources.

To further illustrate the mismatch mentioned above, we calculated the ratio of the GFG implementation area to the SCE from 2000 to 2015 (RGS), to compare the GFG implementation areas among counties in Yan'an under the premise of achieving the same SCE. The RGS value of Wuqi is 1.836, which is 17.49 and 9.37 times as big as that of Yanchang and Yichuan, respectively. That is, under the premise of achieving the same SCE, the GFG implementation area in Wuqi needs to be much higher than in other counties. If the GFG implementation intensity can be formulated and adjusted according to the SCP in each county, the implementation efficiency of GFG can be greatly improved, so as to achieve better SCE.

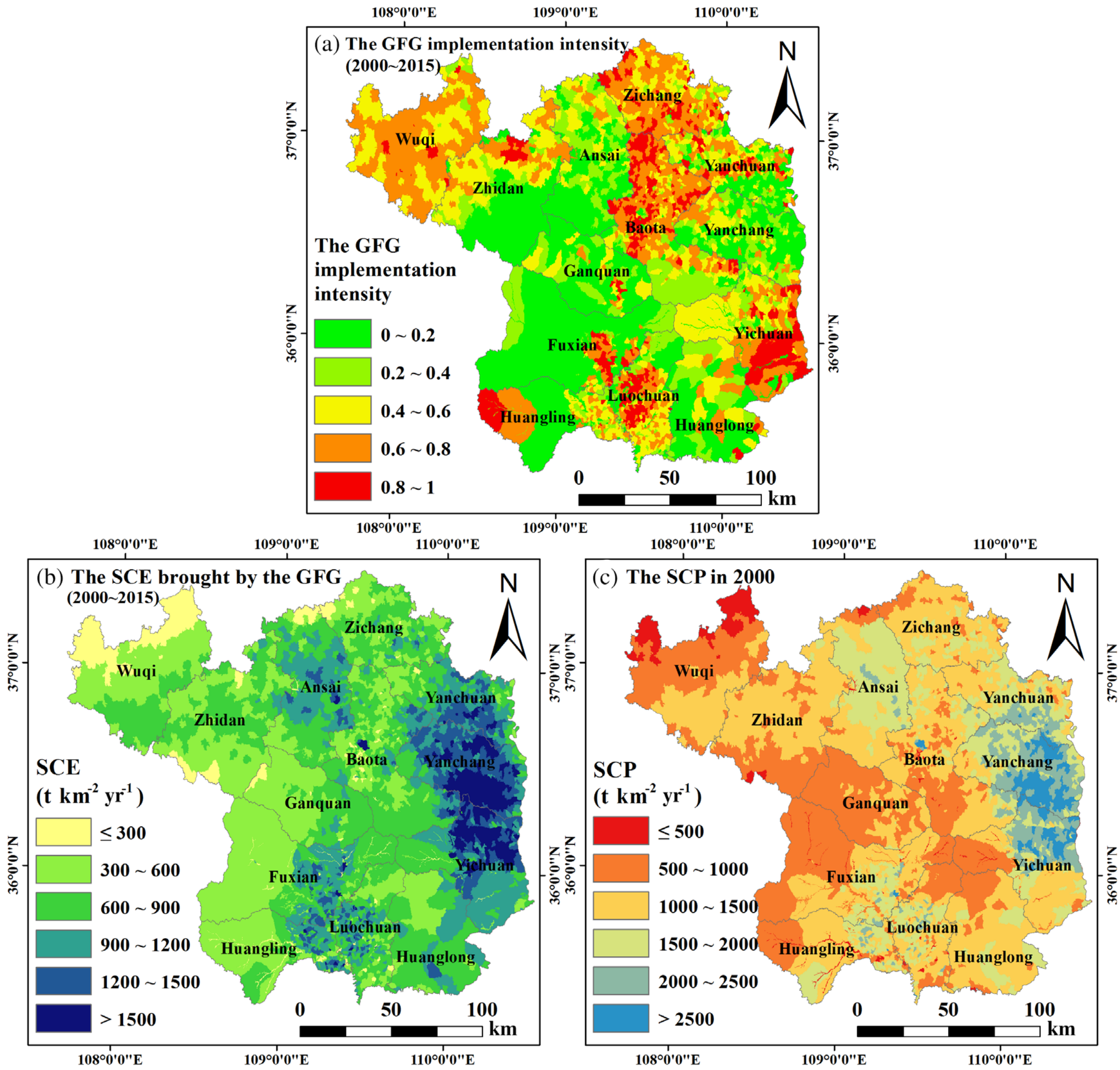

FIGURE 5 (a) The Grain for Green (GFG) implementation intensity (2000–2015); (b) The soil conservation effect (SCE) brought by the GFG (2000–2015); (c) The soil conservation potential (SCP) in 2000 [Colour figure can be viewed at wileyonlinelibrary.com]

4.3 | The GFG strategy based on the SCP

The main purpose of the GFG in Yan'an is to control soil erosion and enhance the SCE. Only by adjusting the GFG implementation intensity to the SCP can a better SCE be achieved. Therefore, in order to optimize the GFG's programme/policy design and project layout, the SCP should be taken into account first. Based on the SCP of each village in 2015, we calculated the priorities for all villages in the future GFG project implementation. According to the quantitative characteristics of the SCP in 2015, we set the SCP threshold to divide the future implementation of GFG into three levels: high-level regions (SCP > 800 t km^{-2} yr^{-1}), mid-level regions (500 < SCP≤800 t km^{-2} yr^{-1}), and low-level regions (SCP≤500 t km^{-2} yr^{-1}). Figure 6 provides the classification and spatial distribution of the levels.

For different levels in Figure 6, different implementation strategies for the GFG should be adopted. High-level villages are concentrated in the east, northeast, and south of Yan'an, which will get the best SCE through the GFG. These regions should be taken as the most suitable regions for the GFG implementation, and the GFG should be continued to perform large-scale artificial restoration of vegetation. The distribution of mid-level villages is similar to that of high-level regions, but the scope is wider. The GFG implementation in these regions should be lower than that of the high-level regions, and it is recommended to conduct moderate artificial vegetation restoration. In the process of formulating the strategies for the GFG, it is necessary to pay attention to the overall coordination between mid-level and high-level regions, so as to achieve economies of scale and reduce costs. Low-level regions are mainly distributed in the middle and northwest. In these areas, the SCE brought by the intensive artificial vegetation restoration in the past was not significant, and the GFG implementation in these areas should be gradually reduced in the future. Besides, natural restoration should be preferred in these regions with the strengthening of environmental management and protection.

TABLE 3 Ranks of the Grain for Green (GFG) implementation intensity, the soil conservation effect (SCE) brought by the GFG, and the soil conservation potential (SCP) in 2000 at the county level

County	The GFG implementation intensity	Rank	The SCE brought by the GFG (t km^{-2} yr^{-1})	Rank	The SCP in 2000 (t km^{-2} yr^{-1})	Rank
Ansai	0.256	12	853.930	4	1,522.564	4
Baota	0.694	1	745.509	7	1,232.594	8
Fuxian	0.330	9	674.398	8	1,129.961	10
Ganquan	0.275	11	572.929	12	865.670	12
Huangling	0.427	8	615.594	9	1,195.142	9
Huanglong	0.236	13	779.665	5	1,261.420	7
Luochuan	0.595	4	754.098	6	1,262.177	6
Wuqi	0.633	3	430.918	13	822.888	13
Yanchang	0.316	10	1,367.809	1	2,138.511	1
Yanchuan	0.476	7	969.693	3	1,638.593	3
Yichuan	0.566	5	1,128.938	2	1,665.547	2
Zhidan	0.476	6	575.861	11	1,048.796	11
Zichang	0.662	2	611.076	10	1,263.172	5

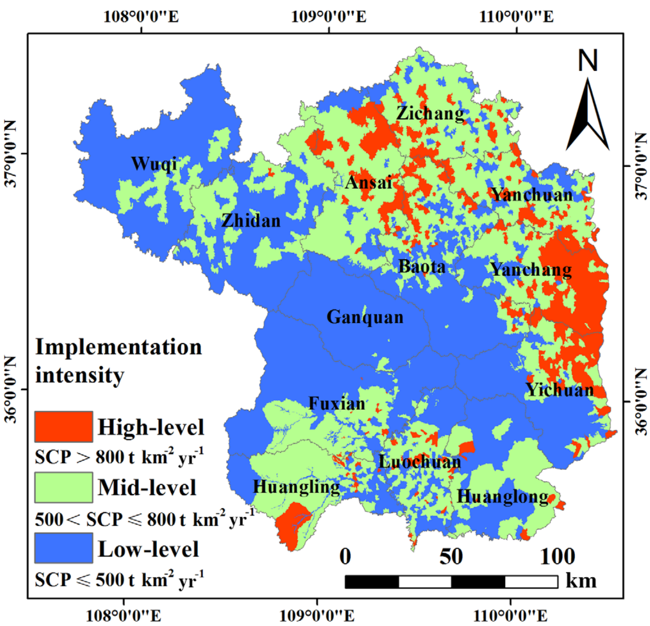

FIGURE 6 The implementation intensity levels of the Grain for Green Programme (GFG) based on the soil conservation potential (SCP) for different villages in the future [Colour figure can be viewed at wileyonlinelibrary.com]

5 | DISCUSSION AND IMPLICATIONS

5.1 | Necessity and importance of the GFG implementation evaluation

As a widespread ecological problem in the world, the soil erosion has a negative impact on the ecological environment and social development (Jiang, Zhang, Zhang, & Wang, 2019; Kong et al., 2018; Sartori et al., 2019; Xiong, Sun, & Chen, 2018). China is a country heavily affected by soil erosion, especially in the Loess Plateau (Du, Xue, Wang, & Deng, 2015; Liu & Liu, 2010; Xi, Zhao, Wang, & Zhang, 2017). Soil erosion in the Loess Plateau not only caused agricultural degradation and farmers' poverty, but also threatened the ecological security of the Yellow River Basin (Heerink, Bao, Li, Lu, & Feng, 2009; Jiao, Wang, Zhao, Wang, & Mu, 2014; Li et al., 2012; Sun et al., 2014). In the Loess Plateau, the goal of the GFG is to prevent the severe soil erosion and reduce the sediment content in the Yellow River (Wang, Fang, Shi, & Lu, 2018; Zhou, Gan, Shangguan, & Dong, 2009). The GFG has had positive and far-reaching effects on the ecological environment and economic development in relevant regions over the past 20 years (Gao, Liu, Li, & Shi, 2020; Jia et al., 2014). The vegetation restoration brought by the GFG has effectively controlled the soil erosion, which is generally agreed (Fu et al., 2011; Jiang, Zhang, Wang, et al., 2019; Liang, Jiao, Tang, Cao, & Li, 2020). Yet this study shows that despite the GFG has played a positive role in previous soil conservation practices, there are certain shortcomings, such as the policy dislocation, and the low efficiency in the implementation of GFG. In some regions, the implementation of GFG has cost a lot, while the SCE is very limited. This actually caused underutilization and waste of resources. These problems should be well considered in the future implementation of GFG.

5.2 | Innovation and advantages of the SCP model

Taking the vegetation restoration potential as the core variable, the SCP model is proposed based on the RUSLE, which is the primary highlight and innovation of this study (Xu et al., 2020; Zhang, Xu, et al., 2019). The room for improvement of soil erosion control in various regions can be measured through the SCP model (Gao et al., 2016). It was found that the GFG implementation intensity should be proportional to the SCP. Therefore, based on the SCP map of Yan'an in the past obtained by the SCP modeling, it can be judged whether the GFG implementation intensity in a region was moderate.

In addition, the most suitable layout and scale of the future vegetation restoration can be determined by mapping the current SCP of various regions. The SCP should be a key indicator for improving the efficiency of the GFG implementation in the future. As a result, the SCP model can provide powerful support for both evaluation and planning of the ecological project.

The SCP model overcomes the shortcomings of traditional soil erosion control evaluating methods, which simply considering the reduction of soil erosion in the past (Deng et al., 2019; Fang & Sun, 2017; Subhatu et al., 2018). By using the SCP model, we can not only obtain the soil erosion reduction, but the maximum capacity of vegetation restoration, thus can formulate corresponding GFG strategies for different regions to improve the effectiveness of GFG implementation (Gao et al., 2016). The proposal and application of the SCP model can provide a new understanding of the relationship between the GFG and the soil conservation, as well as a new way for the optimization of GFG in the future.

5.3 | Design of the DIM for the GFG

The relationships among the SCP, the GFG implementation intensity, and the SCE were discussed in detail in Section 4. It is found that the match between the SCP and the GFG implementation intensity is the key to maximizing the SCE. However, the implementation of the GFG is not a once and for all (Geng et al., 2019). In fact, China has implemented two phases of the GFG (Su, Wang, & Shangguan, 2017; Wu et al., 2019), and is currently preparing to implement the third phase. Furthermore, while the soil erosion is being reduced, natural conditions such as humidity and temperature are also changing, resulting in the SCP in a region also constantly changing (Cao, Wu, Yu, & Wang, 2019; He, Zhao, Wang, Wang, & Zhu, 2018; Kong, Miao, Duan, Lei, & Li, 2018). Therefore, adjusting the matching degree of the GFG implementation intensity and the SCP based on the maximization of the SCE is a dynamic process. In other words, at each current stage, the GFG implementation intensity should be formulated based on the latest SCP. Taking the study area of this research as an example, the DIM according to the SCP is given in Figure 7, which is a specific implementation process of dynamic adjustment for the GFG.

It is first necessary to calculate the SCP in different regions. If the SCP is higher than 800 t km^{-2} yr^{-1}, the strategy of 'large-scale artificial vegetation restoration' is adopted; If the SCP is between 500 and 800 t km^{-2} yr^{-1}, the strategy of 'moderate artificial vegetation restoration' is required; and if the SCP is not higher than 500 t km^{-2} yr^{-1}, the strategy of 'natural restoration' should be adopted. After the GFG implementation of the first round, the SCP should be evaluated again, and adopting corresponding recovery strategy according to the newest SCP, and that cycle repeats. Until the average soil erosion in all regions falls below 500 t km^{-2} yr^{-1}, the end goal is achieved, that is, the restoration of artificial vegetation can be ended, and the natural cycle of vegetation can be started.

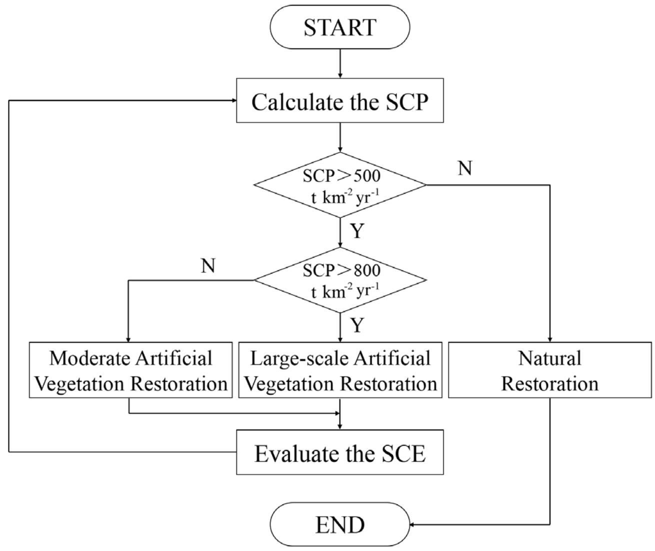

FIGURE 7 The dynamic implementation mechanism (DIM) for the Grain for Green Programme (GFG) based on the soil conservation potential (SCP) and the soil conservation effect (SCE)

6 | CONCLUSIONS

Taking Yan'an City as an example, this study evaluated the implementation effect of the GFG from the perspective of soil conservation and its potential. By constructing the SCP model and exploring the relationship between the GFG implementation intensity and the SCE in space, some problems were found in the implementation of GFG in the past, and the causes of these problems were also analysed. On this basis, suggestions were made for the implementation of GFG in the future. The conclusions of this study are as follows.

1. Since the implementation of GFG, the soil erosion in Yan'an has been controlled on the whole. However, there is a spatial mismatch between the GFG implementation intensity and the SCE, indicating the implementation of the GFG was not well planned in the past. The imbalance of input and output in some areas leads to the failure in achieving the optimal soil conservation effect.
2. The newly proposed SCP model in this study can not only provide a tool to calculate the potential for soil conservation, but also help to explain the low efficiency of the GFG in the past. It might lead to inefficient results if the GFG was intensively implemented in regions with low SCP. In such a case, the SCE achieved will be quite limited even with a high-intensity GFG implementation. It is suggested in this study that more attention should be paid to the SCP before the make of the ecological policy, and the implementation intensity of the GFG project should be matched to the SCP.
3. The DIM is proposed based on the analysis of the relationships among the SCP, the GFG implementation intensity, and the SCE. Firstly, according to the SCP for Yan'an in 2015, three implementation levels for the GFG in the future were divided, and corresponding optimization schemes were formulated for these three levels. And then, policymakers can adjust the GFG strategies

to the changes of the SCP in the future, so as to ensure the high efficiency of soil erosion control, and achieve the sustainability and effectiveness of the GFG. This mechanism can also provide a reference for other ecological restoration measures.

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DATA AVAILABILITY STATEMENT

The meteorological data, soil data, topographic data, vegetation index data, and population data are publicly accessible, and the data sources are given in Section 3.1. Other data and models used during the study are available from the corresponding author by request: (a) the ^{137}Cs data are from Wang et al. (2009) and Sun et al. (2014); (b) the software tool for the calculation of vegetation restoration potential is from Zhang, Xu, et al. (2019); and (c) for process data, please get in touch with the corresponding author of this paper.

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ENDNOTE

[1] The *mu* is a unique area unit in China that mainly used for land measurement, 1 *mu* equals 1/15 hm^2.

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