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RESEARCH ARTICLE

Target areas for harmonizing the Grain for Green Programme in China's Loess Plateau

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Abstract

Widespread land degradation has stimulated the implementation of a large-scale ecological restoration programme in China's Loess Plateau—the Grain-for-Green Programme (GFGP). This programme has substantially increased vegetation cover and served to control soil erosion, but threatened regional food supply due to widespread cropland conversion. Consequently, a strategy balancing green and grain land uses is required. Here, we establish a dominance index of ecosystem services by quantifying the economic value of four key ecosystem services (net primary productivity, soil conservation, water yield, and food production), by combining spatially explicit datasets and census data. Using the dominance index, we identify the optimal areas to target for GFGP in the Loess Plateau. The identified areas (target areas) were the transition zone from low to high value of ecosystem services (ESV). These areas exhibited low grain productivity in addition to having the highest potential for soil conservation. Compared with other regions of the Loess Plateau, the loss of grain production due to cropland conversion in these target areas could decrease by 42%, whereas ESV could increase by 33%. Therefore, despite the fact that over the past 15 years (2000–2014) in these target areas more cropland was converted into ecological use (i.e. forest/grassland), there is still a need to strengthen ecological restoration in this region in the future. This study proposed a strategy for balancing green and grain from a spatial perspective, which could potentially solve land degradation issues and the tradeoff between ecosystem services in a more beneficial and targeted way.

KEYWORDS
cropland conversion, ecological restoration, ecosystem services, land degradation, Loess plateau

1 | INTRODUCTION

Ecosystem provides multiple services which ensure human well-being (Gamfeldt et al., 2013; Wu et al., 2017). Land use/land cover change can alter ecosystem functions, and are considered as one of the most important drivers of ecosystem services change (Jiang et al., 2016; Petz et al., 2014; Song et al., 2015; Wang et al., 2015). During the past decades, however, intensive interference from human activities (e.g. extensive deforestation, cropland and urban expansion, etc.) has dramatically changed landscapes, causing land degradation to be a common issue worldwide (Millenium Ecosystem Assessment, 2005; Willemen et al., 2018; Sagar et al., 2017). To improve human well-being and to change the degraded ecosystem and environment, ecological restoration programmes have been launched on a global scale (Willemen et al., 2018). Correspondingly, increasing interest has been focused on temporal and spatial changes of ecosystem services in the context of ecological restoration (Lu et al., 2012; Jiang et al., 2016; Li et al., 2016a). However, these theoretical ideas need to be incorporated into land-use planning and decision making. Spatial analysis is a useful tool linking science and decision-making, which can generate major gains from ecosystem services in a more beneficial and targeted way (Bateman et al., 2013).

The Chinas Loess Plateau is one of the hotspots of global land degradation (Wang et al., 2018). Historically, this region has suffered from severe soil erosion, making the Yellow River having the highest sediment loads in the world (Zhao et al., 2013; Li et al., 2016b; Wang et al., 2016). To prevent further land degradation and to mitigate increasing soil erosion, the Chinese government implemented a large-scale ecological restoration programme in 1999—the Grain-for-Green Programme (GFGP), which became the largest reforestation scheme attempted globally (Chen et al., 2015; Hua et al., 2016). This programme was designed to increase vegetation coverage and control soil erosion through returning farmland to forest or grassland (Sun et al., 2015; Zhang et al., 2016). Since its implementation, the government has directly invested 191.8 billion RMB (approximately US$28.8 billion) in the GFGP, and the projected investment will be over US$40 billion by 2050 (Feng et al., 2013). Currently, the GFGP has directly involved more than 120 million farmers (about 32 million households) (Liu et al., 2008; Lu et al., 2012; Ouyang et al., 2016). Liu et al., (2008) reported in 2008 that the area under vegetative cover produced by trees and grass in China was planned to increase by 32 million ha by 2010.

As expected, remarkable environmental changes have happened in the decades following implementation of the GFGP. For instance, vegetation cover in the Loess Plateau has been close to 60% with almost doubled increase between 1999 and 2013 (Chen et al., 2015). Recovery of natural vegetation in combination with other soil conservation practices has been effective in controlling soil erosion (Liu et al., 2008; Zhang et al., 2016). River annual sediment load has significantly decreased (Wang et al., 2016; Zhao et al., 2013). Further, the GFGP offers considerable potential for carbon sequestration, with an estimated 96.1 Tg of carbon sequestered from 2000 to 2008 (Feng et al., 2013). However, the GFGP is controversial due to the adverse effect on other ecosystem services, mainly on food production (Chen et al., 2015). The evidence has shown that the cropland converted into ecological use between 1999 and 2006 resulted in a 56% decrease in the total acreage of China's cropland (Wang et al., 2013). During 2000–2010, a 25% increase in vegetation cover came at the expense of 1.6 million ha of rainfed cropland on the Loess Plateau (Feng et al., 2016), causing a potential food loss of 2.8 million tonnes. By 2013, 9.27 million ha of farmland nationwide had been converted to forestland or grassland, which accounted for 6.9% of China's total farmland area (Wang et al., 2017). Such large conversions have created a potential conflict among land use types. Many studies have demonstrated the trade-offs between ecosystem services and food provision in the Loess Plateau (Lu et al., 2012).

A new expansion plan of GFGP was launched in September 2014, which will create greater challenges to balancing green and grain land uses. Currently, there are no available practical guides to inform planners regarding the spatial optimization of land use and management in the Loess Plateau. The present study fills this gap by quantifying the value of ecosystem services (ESV) and their spatially explicit characteristics. In this study, we select for evaluation the following three ecosystem services most appropriate for the Loess Plateau: (a) vegetation productivity (net primary productivity, NPP), which has the benefits of sequestering carbon from the atmosphere, releasing oxygen to the atmosphere, and thereby helping to regulate the climate; (b) soil conservation (SC) related to soil erosion (which was the initial goal of GFGP); and (c) water security, specifically, water yield (Q) related to the issue of serious water scarcity, and examine their ESV. The selection of these ecosystem services is based on the most important issues for the study area, which are vegetation degradation, severe soil erosion and serious water scarcity (Su & Fu, 2013). As well, we investigate the effects of the widespread loss of cropland on regional food security. Finally, we identify the geographical location of priority areas of future GFGP planning on the Loess Plateau. The objective of our research is to present a promising scheme for balancing green and grain land uses from a spatial perspective by answering the following questions: (a) What are the spatial patterns of ecosystem services gains when cropland conversion occurs? (b) How does cropland conversion affect the regional food provision? (c) Where are the regions with minimal food losses and maximum ecosystem services gains located?

2 | MATERIALS AND METHODS

2.1 | Study area

The Loess Plateau is located in the middle reaches of the Yellow River Basin, which encompasses seven administrative provinces (specifically, Gansu, Inner Mongolia, Ningxia, Qinghai, Shaanxi, Shanxi and Henan), and covers an area of 640,000 km^2. The average annual precipitation varies from 144 mm in the north to 790 mm in the south, and is mainly concentrated from June to September (Figure 1). The average annual temperature ranges from 6 to 14°C. The soil is predominantly loess with rich nutrients, suitable for agricultural production. However, most of soil texture ranges from fine silt to silt, which is vulnerable to erosion (Li et al., 2016c). Most of the sediment load of the Yellow River (nearly 90%) is eroded from the Loess Plateau (Wang et al., 2007; 2016). This region is widely known to have the most severe soil erosion in the world prior to the GFGP (Fu et al., 2011; Ouyang et al., 2016; Zhao et al., 2013). The Loess Plateau has three zones of erosion: (a) wind erosion zone in the northwest, (b) water erosion zone in the southeast, and (c) wind–water coupled erosion zone. Among these three zones, the wind–water coupled erosion zone has the most severe erosion, where the erosion occurs year round. Wind erosion in this region occurs predominately in winter and spring, and water erosion occurs predominately in summer and autumn (Tsunekawa et al., 2014).

2.2 | Data sources

Daily precipitation data from 2000 to 2014 were obtained from the China Meteorological Data website (http://data.cma.cn). After calculating the mean monthly and annual precipitation, the point-based meteorological data were spatially interpolated to produce continuous raster images with a spatial resolution of 1 km based on a 1-km resolution digital elevation model layer (He et al., 2017).

The annual NPP and monthly actual evapotranspiration (ET_a) over the Loess Plateau (2000–2014) were estimated from MODIS data products (MOD 17A3 and MOD 16A2, respectively) obtained from the United States Geological Survey (USGS; http://glovis.usgs.gov/) at 1 km resolution.

Land cover data from the Loess Plateau during the GFGP (in 2000, 2005, 2010 and 2014) with a resolution of 1 km were

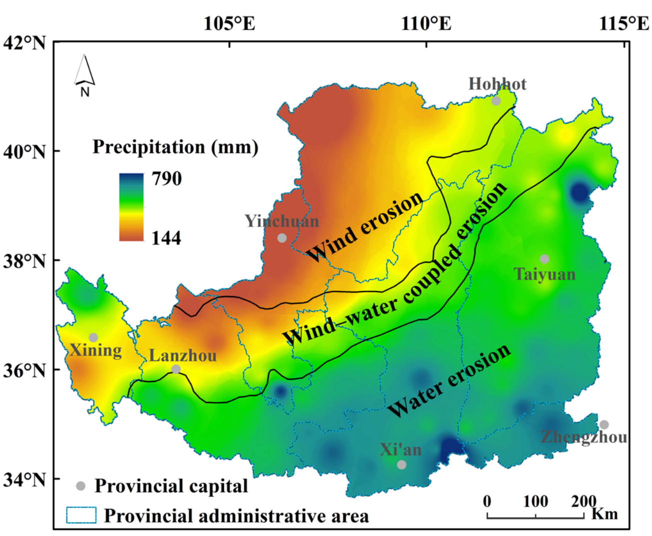

FIGURE 1 Location of the study area and its geographical features [Colour figure can be viewed at wileyonlinelibrary.com]

extracted from LANDSAT images to reveal the land cover changes over this time. Soil data were derived from World Soil Information (ISRIC) (http://www.isric.org/).

Population and grain yield for each county were obtained from the Statistical Database of Economic and Social Development by the National Knowledge Infrastructure of China (http://tongji.cnki.net). After these statistical data were converted into vector data by using the tool of spatial join in ArcGIS software, they were created as raster data at a 1-km spatial resolution.

2.3 | Analyses

The present study attempted to identify target areas of future GFGP planning on the Loess Plateau in the support of ArcGIS. Spatial overlay was employed in various spatial datasets. Interpolation analysis (Inverse Distance Weighted, IDW) was used for establishing grid data of precipitation (Figure 2). We assumed a land-cover scenario where all present cropland areas (1 km by 1 km grid cells) were converted into forestland, called the ‘all forest’ scenario. Then ecosystem services and food loss in the coming decades were assessed under the baseline scenario. Here, conversion of cropland to grassland has been negligible. The GFGP came to an end in 2010 and the areas converted to grassland were not available during the trial period (i.e. before 2002). However, from 2002 to 2009, the total area of land converted into grassland was only about 3% of the area converted into forestland (Deng et al., 2017). Thus, we did not explicitly consider conversion of cropland into grassland.

By examining land use data for 2000 (starting year of the GFGP) and 2014 (the initial year of the new round of GFGP), we identified the regions with cropland conversions to forestland by using spatial overlay in ArcGIS10.2 software. Then we estimated the average annual changes in NPP, soil conservation, and water yield in these regions over this time (Equation 1). We assumed changes in ecosystem services in the coming decades (15 years) were consistent with these during 2000–2014 when cropland conversion occurs. An implied assumption is that no climate change occurs over this period. Next, we investigated the value of ecosystem services when all cropland areas in 2014 were converted into forestland (Equation 2). In this case, the loss of food production was the grain yield per hectare in 2014.

$$\Delta ES_i = \frac{ES_i^{2014} - ES_i^{2000}}{15} \tag{1}$$

$$ES_i^{Future} = ES_i^{2014} \times \Delta ES_i \tag{2}$$

where: ΔES_i is the change rate of the i^{th} ecosystem service during 2000–2014. ES_i^{2014} and ES_i^{2000} are the value of the i^{th} ecosystem service in 2014 and in 2000, respectively. ES_i^{Future} is the value of the i^{th} ecosystem service in the coming decades.

To enable comparisons among different ecosystem services and food production, the value of these services was estimated by

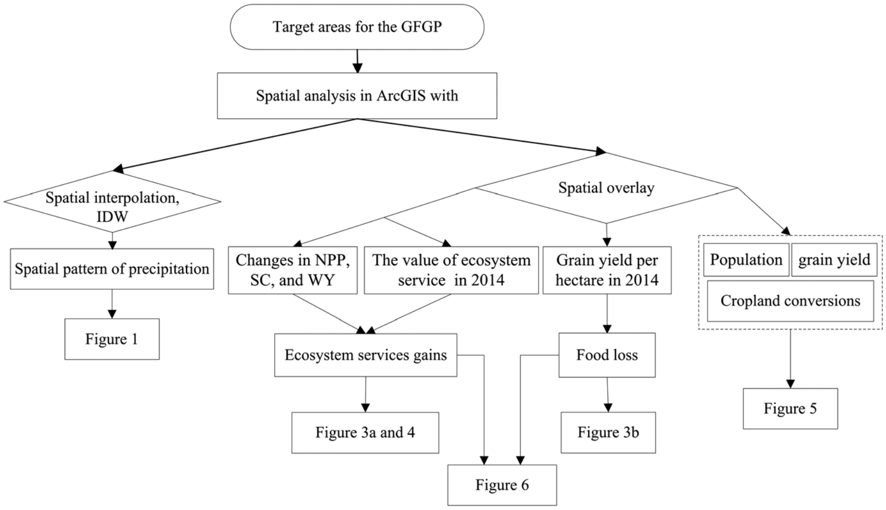

FIGURE 2 The graphic description on various steps to produce results

converting them into economic values. Finally, we identified target areas for the GFGP by measuring the benefit of cropland conversion for each grid cell which was defined as the dominance index of GFGP (A_{GFG}).

$$A_{GFG} = \frac{ESV}{Y} \tag{3}$$

where: Y is the grain yield loss due to cropland conversion, 10^3 US$ km^{-2}. ESV is the net ecological value due to the GFGP, including NPP, SC and Q, expressed in units of 10^3 US$ km^{-2}. Grid cells with an A_{GFG} greater than 5.0 were identified as target areas for the GFGP. These were areas where the ESV was far more than the benefits from yield production.

2.4 | Quantification the value of ecosystem services

We assessed the economic value of NPP, SC, and Q for every grid cell as follows. The economic value of NPP includes the value of carbon sequestration (V_{carbon}) and oxygen release (V_{oxygen}):

$$V_{NPP} = V_{carbon} + V_{oxygen} \tag{4}$$

where: V_{carbon} was estimated by substituting the price of carbon associated with the current standard coal price using the following formula:

$$V_{carbon} = N \times C_s \times 1.474 \tag{5}$$

where: N is the carbon content of NPP; C_s is the standard coal price; 1.474 is the conversion factor between carbon and standard coal.

V_{oxygen} was expressed as the product of the amount of oxygen release ($O_{release}$) and the price of industrial oxygen ($O_{industrial}$). $O_{release}$ from NPP was obtained according to photosynthesis equation:

$$O_{release} = N \times 32 \div 12 \tag{6}$$

Soil conservation services were estimated by calculating the decrease in regional soil loss under the GFGP:

$$\Delta A = A_o - A_v \tag{7}$$

where: ΔA is the average annual soil loss (t ha^{-1}y^{-1}). A_v and A_o are the soil loss with and without vegetation cover separately. The Universal Soil Loss Equation was applied to quantify the amount of annual soil loss (A). According to methods developed for the Loess Plateau (Jia et al., 2014; Jiang et al., 2016), the equation is expressed as:

$$A = R \times K \times L \times S \times (1 - C_v \times P_v) \tag{8}$$

where: R is rainfall–runoff erosivity (MJ mm ha^{-1}h^{-1}y^{-1}) based on monthly rainfall; K is soil erodibility (t ha h ha^{-1}MJ^{-1}mm^{-1}) derived from World Soil Information (ISRIC); L is slope length; S is slope steepness, derived from digital elevation models of the Loess Plateau; C_v is a cover management factor derived from Cai et al., (2000); and P_v is the erosion control practice factor following the slope-based Wener's method (Lufafa et al., 2003). Both C_v and P_v range between 0 and 1. L, S, C_v, and P_v, are all dimensionless. The value of soil conservation was monetized by the national economic loss of soil erosion which is approximately 360 yuan (approximately US$59) tonne^{-1}.

Water yield (Q) was modeled as precipitation (P) minus ET_a, assuming negligible water storage change (Δs) on an annual time scale:

$$Q = P - ET_a + \Delta s \tag{9}$$

Annual ET_a was calculated as the sum of monthly ET_a scaled to the watershed using the ESRI ArcGIS spatial analysis tools. Similar to erosion, we expressed the benefits of water to irrigation as an RMB value per cubic meter using irrigation water pricing.

3 | RESULTS

3.1 | Distribution of the value of ecosystem services

Under the 'all forest' assumption, the spatial pattern of ESV corresponded well with the distribution of precipitation and soil erosion zones (Figure 3a). An evident gradient and transition from northwest to southeast was observed across the study area. The lower ESV was observed in the northwestern part of the Loess Plateau where ESV was less than 300 10^3 US\$ km^{-2} and the annual average precipitation was less than 400 mm. This region corresponded to the wind erosion zone. The transition zone from low to high ESV corresponded to the wind–water erosion crisscross area. In the water erosion zone, ESV was higher (more than 400 10^3 US\$ km^{-2}) and the annual average precipitation was more than 500 mm overall. In comparison with the other two erosion zones, this third area can trade cropland for the higher ESV due to favorable precipitation conditions.

When compared with SC and Q, NPP had a higher ecosystem services value, and thus a similar spatial pattern was observed between NPP and ESV (Figure 4). The value of NPP increased gradually from northwest to southeast. For SC, higher values were located in the central and southwestern Loess Plateau. The value of SC was lower both in the northwestern (e.g. Hetao Plain) and southeastern parts (e.g. Guanzhong Basin) of the Loess Plateau. The value of Q increased under the 'all forest' scenario in most regions. The area of decreased Q was observed to the west of the Loess Plateau, while the area of increased Q was mainly observed in the southeastern part of the study area. Correspondingly, the contribution of Q to ESV was greater in the water erosion zone, while Q had a negative effect on ESV in the wind erosion zone.

3.2 | Food loss

Figure 5 shows the food loss due to cropland conversion from 2000 to 2014. The potential grain production loss caused by the GFGP

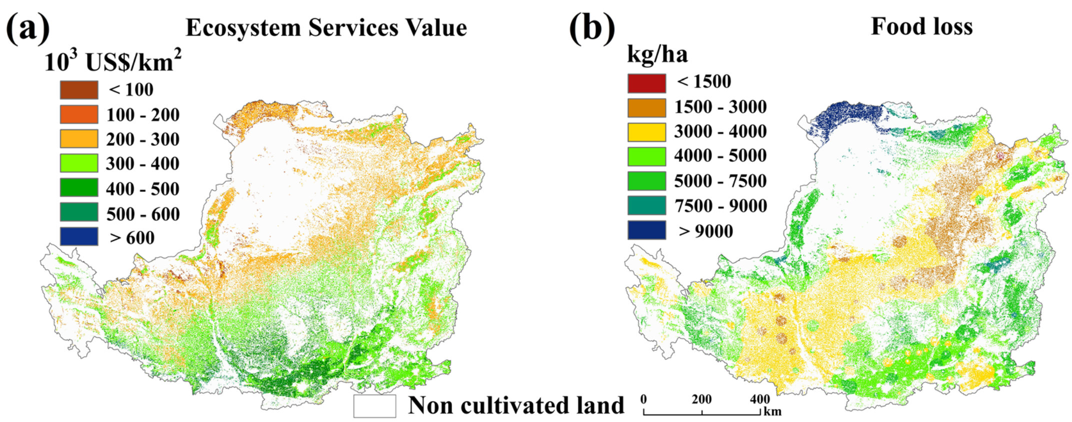

FIGURE 3 Distributions of ecosystem-services value (ESV) (a) and food loss (b) under the 'all forest' scenario on the Loess Plateau. (a) ESV assumes that all present cropland areas are converted into forestland based on land use in 2014. (b) Grain yield per hectare was used to reflect the regional grain productivity, and represented food loss after cropland conversion [Colour figure can be viewed at wileyonlinelibrary.com]

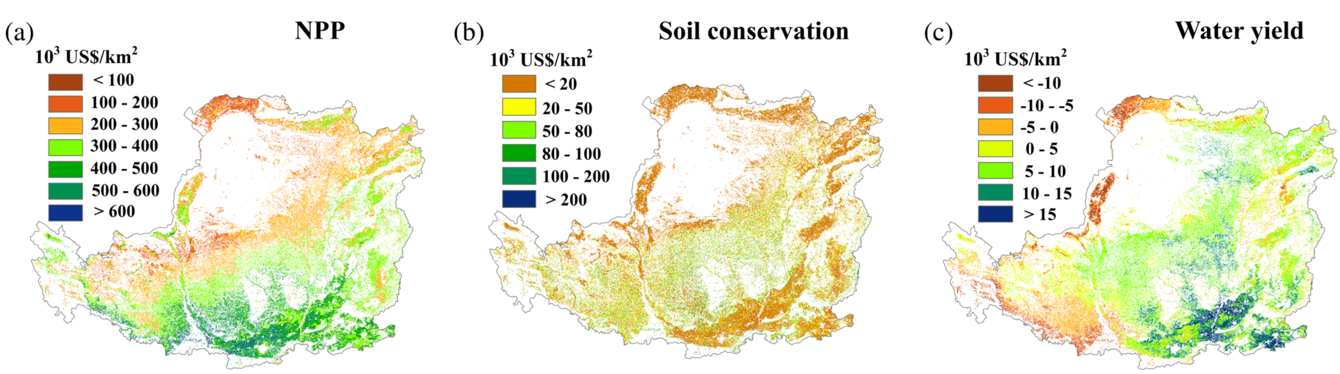

FIGURE 4 Distributions of the value of net primary productivity (NPP) (a), soil conservation (b), and water yield (c) under the 'all forest' scenario in the Loess Plateau [Colour figure can be viewed at wileyonlinelibrary.com]

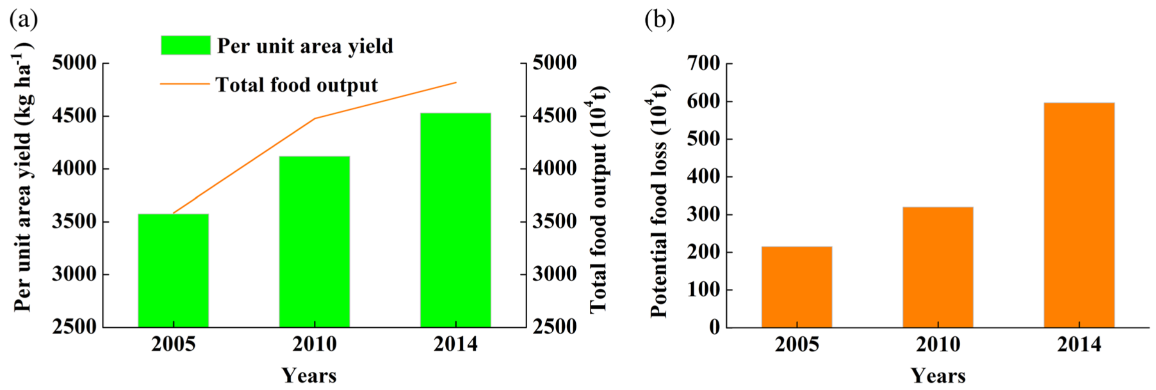

FIGURE 5 Grain production (a) and the potential food loss caused by the GFGP (b) in the Loess Plateau in 2005, 2010, and 2014 [Colour figure can be viewed at wileyonlinelibrary.com]

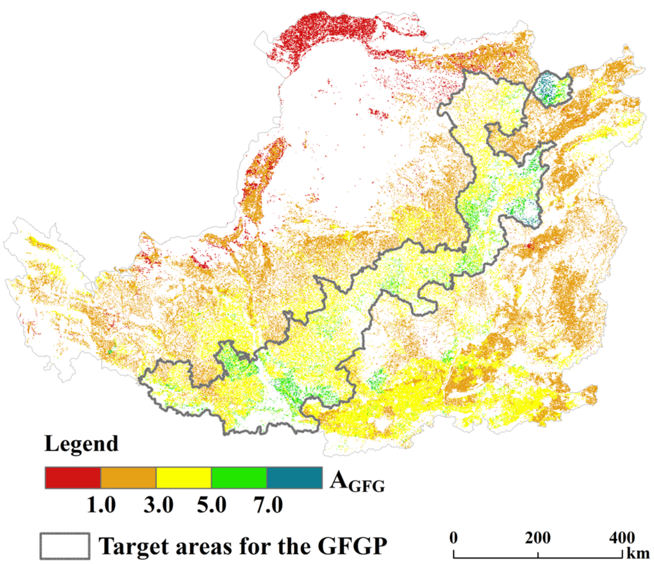

FIGURE 6 Distribution of the dominance index of the GFGP (AGFG) and location of the identified target areas for the GFGP. AGFG is the ratio of the ecosystem service value divided by grain production value on each 1 km × 1 km grid cell. Higher values indicate areas where greater benefits are received from cropland conversion [Colour figure can be viewed at wileyonlinelibrary.com]

increased gradually with the implementation of the GFGP (Figure 5b), although the total output of grain increased because grain yield per hectare increased (Figure 5a). The total food loss in 2014 was nearly 6.0 million tonnes, accounting for 12% of total grain production on the Loess Plateau. This volume of grain could potentially feed 14.9 million people, following the food security standard of the FAO of 400 kg per capita. This loss of grain production equates to a corresponding reduction in the mean annual grain self-sufficiency rate of 15% in this region and 1% in China.

Under the 'all forest' scenario, the total food loss was as much as 51 million tonnes. Moreover, food loss was high both in the northwestern and southeastern parts of the Loess Plateau, where grain yield per hectare was more than 4000 kg (Figure 3b). The areas with lower food loss were mainly distributed in a belt from the northeast to southwest across the central Loess Plateau where rainfed farming predominated.

3.3 | Location of target areas for the GFGP

The areas with minimal food losses and maximum ESV (A_{GFG} > 5.0) occurred predominately in a belt from the northeast to southwest across the central Loess Plateau (Figure 6), and thus these areas were defined as a target area for the GFGP. This belt included Tianshui, Pingliang and Qingyang in Gansu; parts of Baoji and Yan'an in Shaanxi; and Lvliang, Taiyuan, Xinzhou and Shuozhou in Shanxi. The belt lies in the southeastern fringe of the coupled wind–water erosion zone and the nearby water erosion zone, covering about 18% of the Loess Plateau (0.12 million km^2). The wind–water coupled erosion zone covered 26% of this target area and the water erosion zone covered 72% of the target area, with only 2% of the target area in the wind erosion zone. Compared with other regions of the Loess Plateau, the loss of grain production could decrease by 42% if the GFGP was implemented in the target area under the 'all forest' scenario, while the value of ecosystem services could correspondingly increase by 33%.

In addition, the GFGP has high coverage in the proposed target area where 35% of cropland conversion areas occurred during the 2000–2014 period (Figure S1). Over that period, ESV increased by 42% in the target area, of which NPP, SC, and Q contributed 85%, 14%, and 1%, respectively. By contrast, there was a smaller in ESV (29%) outside the target area. Northwest of the target area, ESV increased by 46%. This was closely related to the NPP change. In the southeastern part of the target area, the increase of ESV was lower (16%). Meanwhile, grain productivity in the target area was lower, and was only 57% of that outside the target area. These findings further confirm that the implementation of the GFGP can bring more benefits to the proposed target area.

4 | DISCUSSION

4.1 | Identification of the location of target areas for GFGP

Given the further expansion of the GFGP, food loss is inevitable due to cropland conversion. However, this adverse effect is not evenly distributed over space. This implies that the loss can be reduced if the spatial planning of GFGP is reasonable. Our results indicated that areas which can gain greater value from ecosystem services while minimizing food losses under the GFGP should be concentrated in a belt from the northeast to southwest across the central Loess Plateau. This finding includes some specific information.

First, grain productivity is low in this region. High grain productivity is mostly found in the southeastern and northwestern Loess Plateau where irrigation is employed. For example, precipitation is low (less than 200 mm) in the Hetao irrigation area located in the northwestern Loess Plateau, but the irrigation water diverted from the Yellow River (amounting to 5.2 billion m^3 per year; Geng et al., 2014) contributes to high grain yield (more than 9000 kg ha^{-1}) (Figure 3b). By contrast, the target area identified in the current study for expansion of the GFGP is dominated by rainfed farming. Agriculture in this region is limited by both the availability and accessibility of water resources, resulting in characteristically low grain productivity. Second, this region tends to overlap with the wind–water coupled erosion zone. Previous studies have reported that the wind–water coupled erosion zone is the center of extremely severe erosion in the Loess Plateau which is influenced by both wind and water forces (Tsunekawa et al., 2014). The climate is characterized as the great intensity of rainfall and heavy rainfall in this region, so that greater runoff will occur as pointed by Sun et al. (2018). As a result, high soil conservation value can be gained under the GFGP. Our results also confirmed that the target areas had the higher value of soil conservation (Figure 4b). Third, the target areas are not characterized by high NPP value, but rather are found in the transition zone from low to high NPP, due to the spatial pattern in China's NPP being mainly influenced by annual precipitation (see Figure 1 and Figure 4a, and Liang et al., 2015). In addition, the value of water yield (Figure 4c) similarly varied spatially due to the combined effects of climate and vegetation.

These results illustrate that we cannot gain high value from every ecosystem service when GFGP is implemented in the identified target areas. However, determining the optimal areas for future implementation of GFGP in the Loess Plateau should be done by considering the benefits of multiple ecosystem services. Note, our emphasis on the specifically identified target area in this study does not imply that other regions are less important. For non-target areas, the core objective should also be to address the relationship between food production and environmental sustainability and to ensure environmentally friendly land use. This study has, however, identified the region where future implementation of GFGP will likely provide the greatest benefits.

4.2 | Uncertainty in the monetary value of ecosystem services

In a spatially explicit context, monetary valuation can more precisely identify key ecological restoration areas than conventional ecosystem services assessments. Otherwise, stakeholders tend to over-emphasize benefits from certain services over others, which can result in undesirable land uses or ecological restoration (Strand et al., 2018). For instance, recent revegetation has approached sustainable water resource limits in the Loess Plateau (Feng et al., 2016), implying that the GFGP strategy needs to be adjusted, although it did achieve the goals of increasing vegetation cover and controlling soil erosion. Monetary valuation can assist policy-makers in collaboratively managing different ecosystem services, including priced services and unpriced services, thus providing the basis for both economic and environmental sustainability.

However, estimating ecosystem services values is challenging (Liu et al., 2008; Strand et al., 2018). The use of many parameters, complex ecological processes, and heterogenous data sources causes measurement inaccuracy (Strand et al., 2018; Xie et al., 2017). For instance, data on food production in our study came from statistical data due to geospatial data limitations, while NPP and water yield were based on spatially explicit datasets. These introduced uncertainty into our results. Fortunately, this study focused on the spatial planning of GFGP, and did not focus on the evaluation on the total economic value of ecosystem services. Our aim in estimating ecosystem services values was to enable comparisons among different ecosystem services. By using the market prices of ecosystem services, we employed a dimensionless index to identify the target areas, which mirrored the spatial trend in ecosystem services gains, and thereby avoided the irrationality of results caused by the inaccuracy or imperfection in valuation and measurement. Hence, our study provided a more reliable valuation result than most other studies based on total value estimates. We believe that our approach is applicable for land use decision-making elsewhere in the world.

4.3 | Implications for land-use planning

The sustainability of the large-scale GFGP remains controversial and creates concern among policy makers, farmers, and environmental managers. We cannot answer questions about future GFGP implementation based solely on this spatial analysis. Nonetheless, spatial information can optimize current ecological restoration planning and strategies by defining priority areas for ecological management (Li et al., 2016a), thus providing a critical pathway to regional sustainable management. During the past 15 years, more cropland has been converted into ecological use (forest/grassland) in the target area than in non-target areas (Figure S1), implying that current spatial layout of GFGP is relatively reasonable in the Loess Plateau. However, cropland conversion is still a feasible strategy to strengthen ecological restoration in this region under the expansion of GFGP.

Policy makers need to be cautious when using our maps, since we limit our discussion to cropland conversion. Our approach only considered food loss due to cropland conversion. However, food security has always taken precedence over other questions in China due to its large population. Moreover, the Loess Plateau, even the entire Yellow River Basin, is a net importer of crop (Wu et al., 2018). The potential loss of grain production in 2014 due to the GFGP was nearly 6.0 million tonne (Figure 5b). Had this amount of grain production not been lost, grain self-sufficiency rate in this region could have increased by

15%. Our results could thus be the basis of future related studies for determining grain loss mitigation strategies. Additionally, the scale of a future implementation of GFGP could be established based on the results of our study. Indeed our results give support for the prioritizing future spatial management of GFGP, and demonstrate a new solution for mitigating the adverse effects caused by cropland conversion to forests and grasslands in a more beneficial and targeted way.

CONCLUSIONS

The GFGP has been the main programme aimed at solving land degradation in the Loess Plateau. Spatial targeting of policies can be an effective strategy for promoting the sustainability of GFGP. This study identified target areas to assist with spatial planning for future implementation of GFGP in the Loess Plateau. The results provided the optimal locations where GFGP could be implemented such that high ecosystem services values would result while minimizing food production losses. Compared with other regions of the Loess Plateau, the loss of grain production due to cropland conversion could decrease by 42% in identified target areas, whereas ESV could increase by 33% in such areas. For specific ecosystem services, these regions were distinguished by several features: (a) transition zone from low to high NPP; (b) higher soil conservation value; and (c) low grain productivity. During the implementation of the GFGP from 2000 to 2014, the spatial layout of the GFGP in the Loess Plateau was reasonable. However, cropland conversion by expansion of the GFGP is still needed to strengthen ecological restoration in this region.

Combined with the most important environmental issues related to the debate about the sustainability of the GFGP, the results of our study provide a new perspective to reduce the adverse effects caused by cropland conversions to forests by identifying target areas for the GFGP. These results can assist policy-makers in understanding the costs and benefits of cropland conversion, which can promote better management and planning of land resources. Further, our approach is potentially applicable in other areas of the world undergoing land conversion. Scaling up this analysis would be helpful to solve land use conflicts and the tradeoff between ecosystem services on a global scale.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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