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How to Balance Green and Grain in Marginal Mountainous Areas?

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Key Points:

- Chinese farmers rely heavily on slope cropland and self-sufficient farming in marginal mountainous areas
- Current vegetation restoration strategies are not sufficiently optimized, which may affect farmers' livelihood in mountainous areas
- Planning tailored to local conditions can alleviate the conflict between grain and green, and promote sustainable vegetation restoration

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

China has implemented the world's largest-ever vegetation restoration program in marginal mountainous areas to sustain life on land. However, land competition between the demand for grain and the need for green has threatened sustainable vegetation restoration. Here, focusing on China's marginal mountainous areas with the highest density of slope cropland, we explore the optimal solution in the trade-offs between green and grain. We find that current vegetation restoration strategies are not sufficiently optimized, which may threaten the survival and development of local farmers and in turn destroy existing vegetation restoration achievements. Through adjusting vegetation restoration objectives carefully tailored to local conditions, the population experiencing grain shortages can be greatly reduced by 51–66% (from 18.26 million to 6.29–8.90 million) compared with the current scheme. The optimal design will alleviate the conflict between grain and green, thereby promoting sustainable ecological restoration in China. Our research provides an important reference for the world's mountainous areas to achieve a win-win situation between green and grain.

Plain Language Summary

Vegetation restoration in China has made remarkable achievements in recent years. However, the sustainability of these vegetation restoration programs has been questioned and challenged. Combined with spatial statistics and scenario analysis for analyzing the trade-offs between green and grain, we find that the current vegetation restoration strategies in China's mountainous areas are not sufficiently optimized, which may affect the sustainability of vegetation restoration programs. Vegetation restoration strategies adapted to local conditions can reduce the risk of grain shortage for 9.30–11.97 million farmers, and contribute to a more balanced development and the sustainability of vegetation restoration in mountainous areas.

1. Introduction

The global economy has been growing rapidly at the expense of the deterioration of the environment in the past few decades (Hoang & Kanemoto, 2021; Liu & Diamond, 2005). The trade-offs between economy and environment have a huge impact on the common realization of sustainable development goals (SDGs) in 2030, especially when imbalance impacts on regions were considered (Von Braun & Gatzweiler, 2014). To address these challenges, large-scale vegetation restoration has been carried out globally with an attempt to mitigating global climate change (SDG13), protecting life on land (SDG15), and reducing poverty (SDG1; Adams et al., 2016; Bryan et al., 2018; Ouyang et al., 2016). Generally, vegetation restoration programs concentrate in marginal mountainous areas at the expense of cropland, which will directly affect the grain supply of local farmers (Chen et al., 2015; Dang et al., 2020). While those farmers who are at the margin of subsistence do not benefit much from the economic improvement, they have endured considerable survival pressure triggered by the vegetation restoration programs (Von Braun & Gatzweiler, 2014). Grain shortages, poverty, and inappropriate policies are intertwined and uncoordinated, which in turn threaten the sustainability of vegetation restoration (Cao et al., 2009b, 2021; Doelman et al., 2020). Therefore, understanding the impact of vegetation restoration on grain supply and the reverse effect of grain supply on vegetation restoration is crucial for a more balanced and equal development of marginal mountainous areas and the sustainability of vegetation restoration.

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Slope cropland is generally considered to be the optimal target area for vegetation restoration because of its low grain productivity and high potential for environmental benefit (Uchida et al., 2005). Over 800 million people globally live on slope land, and they continue to practice subsistence-oriented farming (Drees et al., 2003; Meemken & Bellemare, 2020). Fragile ecosystems, primitive transportation and trade systems, and low economic development caused by marginality have forced farmers to rely heavily on slope cropland for their livelihoods (Drees et al., 2003; Liu et al., 2017; Von Braun & Gatzweiler, 2014). Poor farmers are driven into a vicious circle whereby the excessive use of environmental resources to survive leads to environmental degradation that further impoverishes them (Cao et al., 2009b; CMWR, 2010; WCED, 1987). A well-designed vegetation restoration program in these regions could help farmers to achieve demarginalizing and escape from the poverty trap by improving the ecological environment, optimizing agricultural structure, and promoting the transfer of labor (Barbier & Hochard, 2018; Bryan et al., 2018; Suding et al., 2015). However, inappropriate vegetation restoration could also be a threat to the poor farmers in marginal mountainous areas, where the slope cropland is an indispensable environmental resource for basic grain needs to survive the poors (Chen et al., 2015; Feng et al., 2005). Once faced with insufficient grain output and livelihood difficulties, poor farmers have to reclaim the restored slope cropland again (Cao et al., 2009a; Deng et al., 2016), thereby affecting the sustainability of vegetation restoration strategies and resulting in relapses into the vicious circle (Cao et al., 2021). Therefore, vegetation restoration programs need to be more elaborately designed when involved in the trade-offs between green and grain.

In 1999, China launched the first phase of the Grain for Green Program (GGP-1), the largest-ever ecological restoration program worldwide (Ran et al., 2018). By 2014, approximately 500 billion yuan (~US$63 billion) had been invested to convert 90,000 km^2 of slope cropland to forest or grassland (NFGA, 2020). The conversion of large areas of scarce croplands to nonagricultural land has intensified the conflict between grain and green in China's marginal mountainous areas, which has also triggered a debate among researchers about the trade-offs between grain and green (Shi et al., 2020). Xu et al. (2006) studied the effects of GGP-1 on grain prices and yield of surplus land, and concluded that GGP-1 has almost no threat to grain security. Sun et al. (2006) used a driving force model to predict the change of steep cropland and argued that GGP-1 would not cause grain shortages in China. On the contrary, some studies concluded that the greater-than-expected reduction of cropland in GGP-1 (Note S1 in Supporting Information S1) will threaten the livelihood and grain supply for some farmers (Chen et al., 2015; Feng et al., 2005). At the government level, policy makers believe that GGP-1 threatens regional grain security to a great extent (CMNR, 2004). As a response, policy makers have suspended the further implementation of GGP-1 in 2007 (NFGA, 2020). However, the above studies have focused primarily on the impact of vegetation restoration on grain supply and have mostly ignored the feedback of vegetation restoration on the change of grain supply, especially the sustainability of vegetation restoration after grain shortage. Therefore, in the context of large-scale vegetation restoration, the interaction and trade-offs between grain and green in China's marginal mountainous areas need to be further examined.

In 2014, the Chinese government launched the second phase of GGP (GGP-2) to maximize the benefit of good ecological services like carbon sequestration, flood control, and soil conservation attested by the GGP-1 (Liu et al., 2008; Ouyang et al., 2016; Tong et al., 2018). However, regional differences and local conditions were not well considered in formulating clear and detailed standards for vegetation restoration (Note S1 in Supporting Information S1). Additionally, there are no studies to assess the trade-offs between grain and green under the new round of GGP. Given that China's mountainous areas provide grain for hundreds of millions of smallholder households that continue to maintain a low-intensity, low-yield, low-profit, and self-sufficient agricultural production pattern (Cui et al., 2018; Meemken & Bellemare, 2020), it is crucial to assess the impact of current vegetation restoration strategies on grain supply as well as to obtain further feedback regarding different grain risk conditions on vegetation restoration. To fill this knowledge gap, we analyze and predict the impact of vegetation restoration on grain supply, explore how to coordinate the conflict between green and grain, and determine the optimal solution to the trade-offs between green and grain in the mountainous areas of China. Our study will provide valuable guidelines to global mountainous areas endeavoring to achieve SDGs, including climate action, reduced inequalities, and no poverty.

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2. Materials and Methods

2.1. Study Area

To describe the spatial distribution of slope cropland in China, we divided China into eight agricultural regions according to the agricultural regional boundary of the Resource and Environment Science and Data Center of the Chinese Academy of Sciences (http://www.resdc.cn/data.aspx?DATAID=275). The eight major agricultural regions include the Northeast China Plain (NE, 0.80 million km^2), the Northern arid and semiarid regions (NAS, 3.3 million km^2), the Huang-Huai-Hai Plain (HHP, 0.55 million km^2), the Middle-lower Yangtze Plain (MYP, 0.93 million km^2), the Southern China (SC, 0.37 million km^2), the Sichuan Basin (SBS, 0.57 million km^2), the Yunnan-Guizhou Plateau (YGP, 0.81 million km^2), and the Loess Plateau (LP, 0.37 million km^2; Figure 1). The Qinghai-Tibetan Plateau (TP) was not included here due to its low proportion of slope cropland. This study focused on three regions (SBS, YGP, and LP) with the highest proportion of mountainous areas and the most concentrated slope cropland in China (Note S2 and Figure S1 in Supporting Information S1). The average slopes of SBS, YGP, and LP are 20°, 18°, and 15°, respectively. The total population of these three regions (317.5

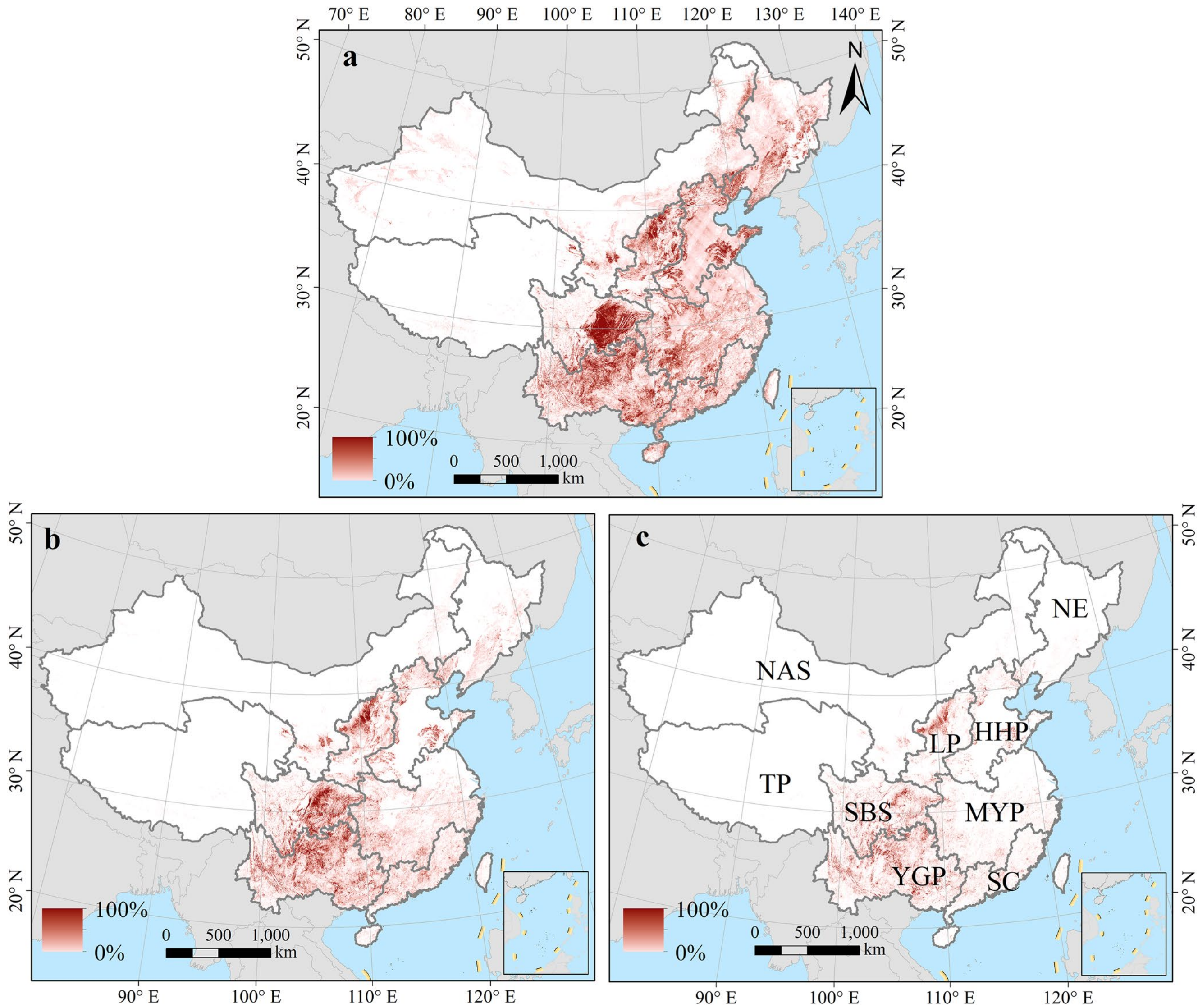

Figure 1. Spatial distribution of slope cropland in China. (a) Cropland with slopes >6°. (b) Cropland with slopes >15°. (c) Cropland with slopes >25°. The colored percentage legend represents the proportion of slope cropland per unit area of land. NE, Northeast China Plain; NAS, Northern arid and semiarid regions; HHP, Huang-Huai-Hai Plain; MYP, Middle-lower Yangtze Plain; SC, Southern China; SBS, Sichuan Basin; YGP, Yunnan-Guizhou Plateau; LP, Loess Plateau; TP, Qinghai Tibet Plateau.

million people) is only 23% of China's population, but its rural poor accounts for 44% of the rural poor population of China (NBS, 2015). According to the National Development and Reform Commission, the three regions accounted for approximately 52% of the GGP-1 effort and approximately 70% of the GGP-2 effort (NFGA, 2020).

2.2. Extraction of Slope Cropland

We used the China Cropland Extent-Product with a resolution of 30 m in the Global Food Security-support Analysis Data (GFSAD; Thenkabail et al., 2012; https://croplands.org/downloadLPDAAC). Compared with other global land use products with a 30-m resolution, this product focuses on providing a more accurate cropland extent, rather than on classifying all land uses. For cropland in China, its overall accuracy is 94% with a producer accuracy of 80% and a user accuracy of 84.2%. Additionally, this product shows a very high correlation with data found in the China Statistical Yearbooks, which further proves its application potential for quantifying the spatial distribution of cropland in China (Teluguntla et al., 2018).

To reduce the burden of downloading and processing the original images locally, we extracted slope cropland in China on Google Earth Engine (GEE) (Gorelick et al., 2017). We first uploaded the GFSAD products to GEE and generated the slope layer using the SRTM terrain data with a resolution of 30 m on GEE. We then superimposed different slopes onto the cropland layer to obtain a slope cropland layer with different slopes. Finally, we calculated the area of slope cropland with different slopes at the county ($n = 2{,}889$), provincial ($n = 31$), and regional levels ($n = 8$) in China on GEE for the follow-up analyses.

2.3. Data Analysis

We collected provincial economic development data from the China Statistical Yearbooks and the China Rural Yearbooks, including the total population (P), urban population (P_{urban}), rural poor population (P_{poor}), illiterate population ($P_{\text{illiterate}}$), per capita GDP (GDP_{pc}), per capita disposable income (PCDI), and per capita consumption expenditure (PCCE). Then, we used Pearson correlation analysis to determine the relationship between the slope cropland area and topographic factors and the above-mentioned economic development factors. To avoid multicollinearity, we used partial least squares regression (PLSR) to further explore the factors affecting the distribution of slope cropland. The appropriate number of components for each PLSR model was determined by cross-validation to achieve an optimal balance between the explained variation in the response (R^2) and the predictive ability of the model (goodness of prediction, Q^2). For models with good predictive ability, the relative importance of each independent variable can be expressed more intuitively and comprehensively by analyzing the variable importance for projection (VIP) values (Shi et al., 2013). Generally, VIP values greater than 1.0 indicate important independent variables, and values lower than 0.5 indicate unimportant independent variables. Additionally, the household's data obtained from China Family Panel Studies (CFPS, http://www.isss.pku.edu.cn/cfps/) was used to analyze farmers' dependence on self-sufficient agriculture. The CFPS is a nationally representative, biennual longitudinal survey, which mainly collects individual-level, family-level, and community-level longitudinal data in contemporary China. We obtained a total of 6,547 household survey data, including total household income, agricultural income, food expenditure, etc. The Pearson correlation was used to determine the impact of household income on the proportion of agricultural income and food expenditure at the household level and to determine the impact of per capita GDP on the proportion of agricultural GDP and the area of steep slope cropland at the county level.

2.4. Grain Yield Model of Slope Cropland

Referring to Land Use Status Survey Technical Regulations issued by the Ministry of Agriculture of China (http://www.moa.gov.cn/), we defined cropland with slopes >6° as slope cropland, and further divided the slope cropland into five categories (6–10°, 10–15°, 15–20°, 20–25°, and >25°). We used the method of Feng et al. (2005) to estimate the grain yield per unit area of slope cropland with different slopes. The regional total grain output is the sum of the grain output of all slopes and can be expressed by

$$G_t = \sum_{i=0}^{5} a_i \times \beta_i \times G_{ave} \tag{1}$$

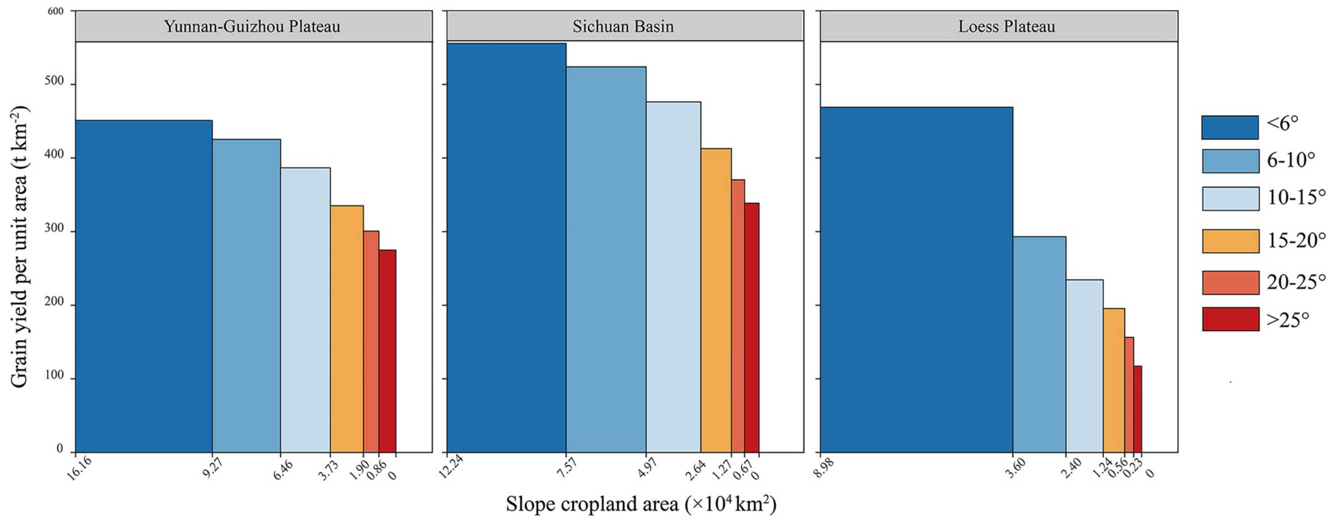

Figure 2. The slope cropland area, grain yield per unit area, and total grain yield in three key regions. The area of each column represents the total grain output of cropland in the corresponding slope range.

where G_t is the total grain output of the region; G_{ave} is the grain yield per unit area of the region, obtained from the National Statistical Yearbook; a_0–a_5 are cropland land areas with slopes <6°, 6–10°, 10–15°, 15–20°, 20–25°, and >25°, respectively (Figure 2); and β_0–β_5 are the ratio coefficients between the grain yield per unit area of different slopes and G_{ave} for the six slope categories (Table 1).

A higher slope will lead to more soil and water loss, which will decrease the organic matter content and further reduce grain yield. We estimated β_0–β_5 using farmer questionnaire data and statistical analysis data in published literature (Feng et al., 2005; Lu et al., 2013).

2.5. Grain Self-Sufficiency Index (GSSI)

Self-sufficiency in grain production is an important index for assessing a region's ability to generate enough grain to support its population. A GSSI relates the grain output to grain consumption. In China, grain self-sufficiency has always been the most important evaluation criterion for grain supply for both policymakers and farmers (Ghose, 2014; Zhang & Cheng, 2016). We used the following formula to calculate the GSSI

$$\mathrm{GSSI} = \frac{G_t}{\mathrm{P} \times \mathrm{k}} \tag{2}$$

where G_t is the total grain output of the region, k represents the per capita grain demand (i.e., 400 kg grain per capita, as proposed by FAO; Liu et al., 2020), and P represents the total population.

2.6. Scenario Simulation

Accurate prediction of population and grain yield per unit area is required to accurately predict the change in GSSI in different situations. The population will not fluctuate much in the short term, so we applied the widely used gray model GM (1, 1) to predict the population change in each region from 2015 to 2030 (Lu et al., 2009; Shi et al., 2020). However, grain yield per unit area is difficult to predict accurately due to the impact of human activities and climate change. To reduce the uncertainty of different prediction methods, we used common grain yield prediction models, including the GM (1, 1) model, linear regression, and logistic regression (Khoshnevisan et al., 2014; Li et al., 2018; Methods in Supporting Information S1). We used the prediction results from the three different models to set the upper and lower limits for grain yield per unit area (Figure S2 in Supporting Information S1). We

Table 1
Description of Main Parameters in Grain Yield Model of Slope Cropland

Parameters	Yunnan-Guizhou plateau	Sichuan basin	Loess plateau
β_0 (<6°)	1.05	1.05	1.20
β_1 (6°–10°)	0.99	0.99	0.75
β_2 (10°–15°)	0.90	0.90	0.60
β_3 (15°–20°)	0.78	0.78	0.50
β_4 (20°–25°)	0.70	0.70	0.40
β_5 (>25°)	0.64	0.64	0.30
G_{ave} (t km^{-2})	432	525	391

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established three basic vegetation restoration scenarios, including not converting cropland to forest or grassland (NC), converting cropland with slopes >25° to forest or grassland (C25), and converting cropland with slopes >20° to forest or grassland (C20). C25 represents the most basic requirements and goals of GGP. This slope threshold was proposed by the 20 years of Grain for Green in China (1999–2020) reported by the government, which is the most authoritative and detailed summary of the GPP (NFGA, 2020). According to this report, the slope threshold should be reduced to further increase the area of vegetation restoration. Referring to the slope classification in previous studies (Lu et al., 2013), we established the second vegetation restoration scenario (C20). Additionally, a large number of check dams on the Loess Plateau have significantly increased its regional grain output (Wang et al., 2011), and more than 56,000 additional check dams will be built on the Loess Plateau by 2030 (NDRC, 2010). Therefore, we established two specific scenarios for the Loess Plateau, including the conversion of cropland with slopes >25° and >20° to forest or grassland and the construction of check dams (C25 + D and C20 + D, respectively). A more detailed description of each scenario and the calculation of GSSI are included in Methods S1 in Supporting Information S1.

According to the report of the National Development and Reform Commission of China, a region or country can be classified as completely self-sufficient (GSSI > 1.0), basically self-sufficient (0.95 < GSSI < 1.0), or capable of achieving an acceptable level of grain self-sufficient (0.9 < GSSI < 0.95; Qiao, 2013). However, when GSSI is less than 0.9, the risk of regional grain shortages will increase (Mukhopadhyay et al., 2018; Simelton, 2011). To ensure that regional grain self-sufficiency is not at great risk, for those regions with a GSSI less than 0.9 in 2015, the GSSI will need to reach 0.9 in the 2015 to 2030 period. For those regions where GSSI was greater than 1.0 in 2015, GSSI should not be less than 0.95 in 2015–2030.

3. Results

3.1. Slope Cropland in China

In 2015, the areas of cropland in China with slopes >6°, >15°, and >25° were approximately 369,000, 104,000, and 21,000 km^2, respectively (Figure S3 in Supporting Information S1). There are pronounced spatial differences in the distribution of slope cropland (Note S3 in Supporting Information S1), in which steep slope cropland (with slopes >15°) is mainly located in the Sichuan Basin, Yunnan-Guizhou Plateau, and Loess Plateau (Figure 1 and Figure S4 in Supporting Information S1). The areas of cropland with slopes >15° and >25° in these three regions combined account for 73% and 79% of all cropland with slopes >15° and >25° in China, respectively. The spatial distribution of slope cropland is highly related to topography and economic development. Correlation analysis results show that slope cropland areas are positively correlated with the average slope gradient, rural poor population (population with a per capita net income of less than 2,300 yuan (~US$288) per year), and illiterate population, and negatively correlated with per capita gross domestic product, per capita disposable income, and per capita consumption expenditure (Figure S5 in Supporting Information S1). PLSR results further show that the average slope gradient, the rural poor population, and the illiterate population are the three primary factors affecting the spatial distribution of slope cropland (VIP > 1; Tables S1 and S2 in Supporting Information S1).

Slope cropland is widely distributed and provides a large amount of grain supply for China's mountainous areas, although its grain yield per unit area is relatively low (Figure 2). Taking the Yunnan-Guizhou Plateau, Sichuan Basin, and Loess Plateau as examples, the grain outputs of cropland with slopes >15° are 11.91, 10.49, and 2.22 million tons (Table S3 in Supporting Information S1), accounting for 17.1%, 18.1%, and 6.6% of the total grain output, respectively (Figure 2). According to the FAO standards of 400 kg yr^{-1} per person, cropland with slopes >15° in the Yunnan-Guizhou Plateau, Sichuan Basin, and Loess Plateau could supply the grain needs of 29.78, 26.23, and 5.55 million people, respectively. In particular, slope cropland and the grain it supplies are more essential for the survival of mountain populations, especially those in poor areas. County-level data in China show that a lower per capita GDP will cause a greater proportion of agricultural GDP (Figure 3b). Additionally, per capita GDP is negatively correlated with the area of steep slope cropland (Figure 3b), indicating that low-income areas are heavily dependent on agriculture and slope cropland, and this degree of dependence deepens with the aggravation of poverty. Through the further comparative analysis of 6,547 households obtained from China Family Panel Studies, we found that agricultural income accounts for 27% of the total household income on average. However, this proportion reached 100% for the poorest households (Figure 3c). Moreover, we also find that food expenditure decreases with declining total income (Figure 3d). These results indicate that the lower the household

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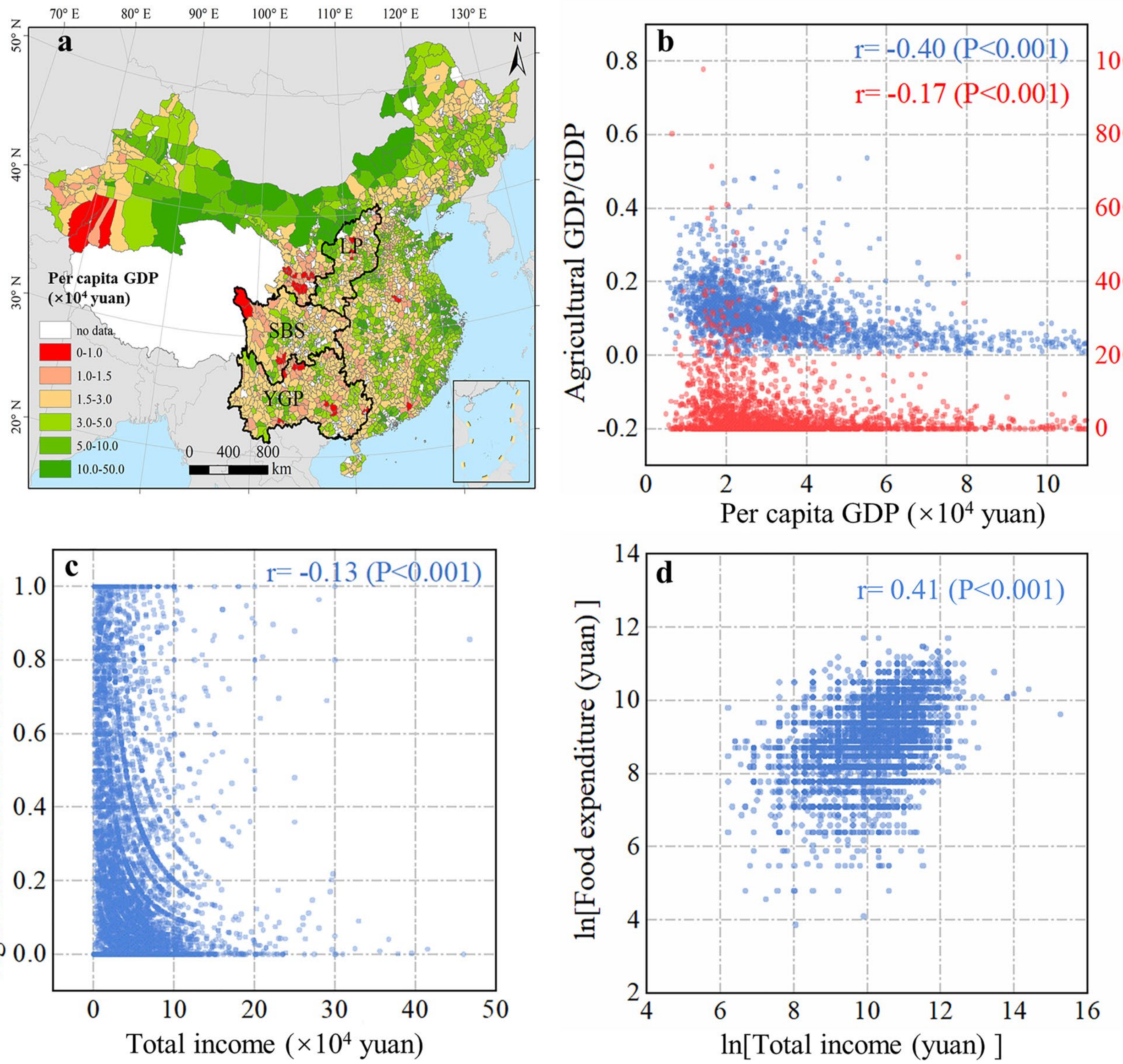

Figure 3. Economic data at county level and household survey level in China. (a) Per capita GDP at county level in China. (b) The relationship between per capita GDP and the proportion of Agricultural GDP at County level. (c) The relationship between total household income and the proportion of agricultural income. (d) The relationship between total household income and food expenditure. The red scatter plots in panel (b) represent the area of steep slope cropland (with slopes >15°) under different per capita GDPs at the county level. SBS, Sichuan Basin; YGP, Yunnan-Guizhou Plateau; LP, Loess Plateau.

income is, the greater its dependence on self-sufficient farming and the lower willingness of purchasing food will be.

3.2. Impact of Greening on Grain Supply

We further analyzed the changes in grain supply under different vegetation restoration scenarios. Considering the spatial distribution of steep slopes and rural poor population, we focused on three key mountainous regions, including Yunnan-Guizhou Plateau, Sichuan Basin, and Loess Plateau (Note S2 in Supporting Information S1), all of which have the largest steep slope areas and account for ~70% of the GGP-2 effort. These three regions also account for 44% of China's rural poor population (NBS, 2015). Further vegetation restoration will aggravate the contradiction between green and grain in these three regions. The actual values of the GSSI for these three regions decreased significantly in the early stage of the first phase of the GGP (GGP-1-E), especially on the Loess

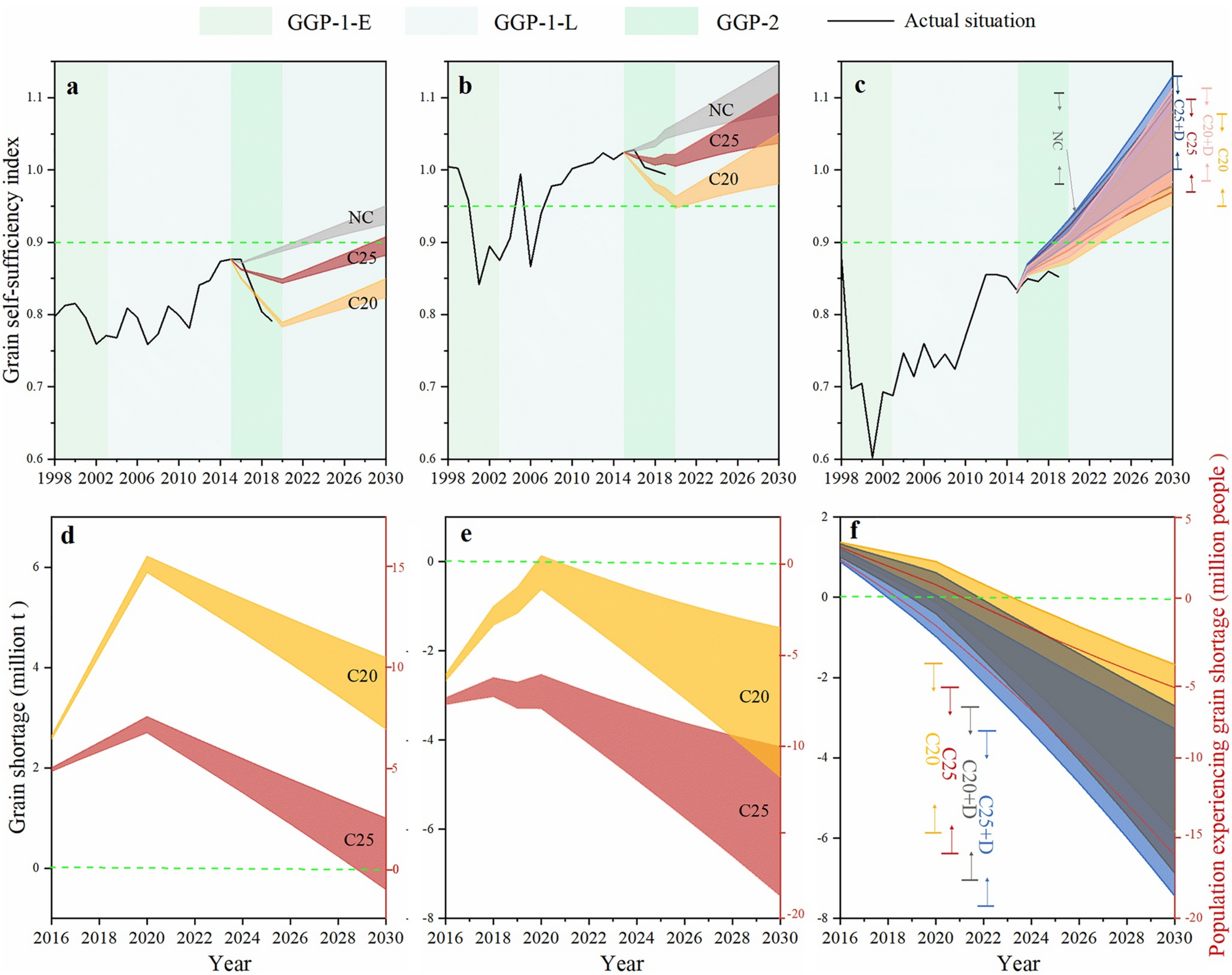

Figure 4. Prediction of grain self-sufficiency index (GSSI), the total amount of grain shortage, and the population experiencing grain shortage in three key regions of China. (a and d) Yunnan-Guizhou Plateau. (b and e) Sichuan Basin. (c and f) Loess Plateau. The total amount of grain shortage and the population experiencing grain shortage are calculated based on the set value of the GSSI (green dotted line). Above/below the green dotted line represents the lack/surplus of grain. The actual situation refers to the current scheme calculated from published Statistical Yearbook data. NC, not converting cropland to forest or grassland; C25/C20: converting cropland with slopes >25°/>20° to forest or grassland; C25 + D/C20 + D: converting cropland with slopes >25°/>20° to forest or grassland in conjunction with check dam construction. GGP-1-E/GGP-1-L, early stage/late stage in Phase 1 of the Grain for Green Program (GGP); GGP-2, Phase 2 of the GGP.

Plateau where the GGP was first implemented. National Yearbook data show that the total grain output on the Loess Plateau dropped from 23.8 million tons in 1998 to 16.7 million tons in 2001, a decline of more than 30%. The corresponding GSSI of the Loess Plateau dropped sharply from 0.88 in 1998 to 0.60 in 2001 (Figure 4c). In the late stage of GGP-1 (GGP-1-L), with the continuous adjustment of policy (Note S1 in Supporting Information S1), the GSSI of the three regions showed a significant upward trend. However, the GSSI values in the Yunnan-Guizhou Plateau (0.88) and Loess Plateau (0.83) were still less than 0.9 even by 2015 (Figures 4a and 4c). With the implementation of the second phase of the GGP (GGP-2), the GSSI of the Yunnan-Guizhou Plateau and Sichuan Basin declined again (Figures 4a and 4b).

Under the NC scenario (not converting cropland to forest or grassland), the grain supply allowed the three regions to gradually become self-sufficient. In contrast, the grain supply under the cropland conversion scenarios will change with varying degrees of risk (Figure 4). From 2015 to 2030, almost all cropland conversion scenarios in the Yunnan-Guizhou Plateau fail to reach a GSSI of 0.9 (Figure 4a). To reduce the population experiencing grain shortages (i.e., the population that is short of grain when the set value of GSSI is not met) caused by cropland conversion, the central government has to continuously provide additional grain supplies to this region. For

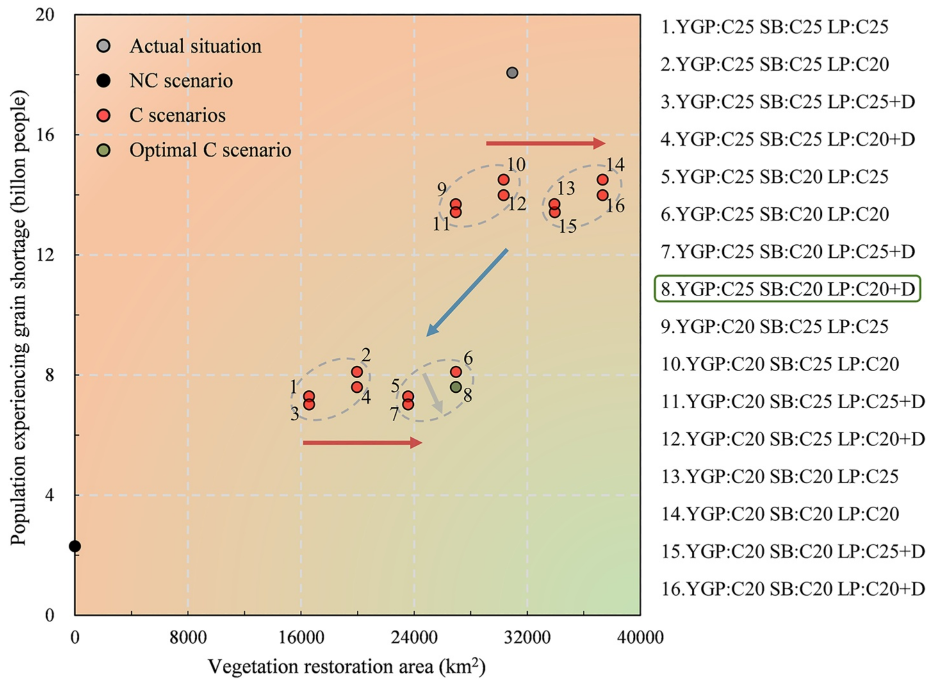

Figure 5. The trade-offs between grain and green. NC/C represents not converting/converting cropland to forest or grassland. Scenarios that fall in the green zone can restore more cropland and have a lower population experiencing grain shortage. The blue arrow represents the scenario in which the Yunnan-Guizhou Plateau (YGP) changes from C20 to C25. The red arrow represents the scenario in which the Sichuan Basin (SB) changes from C25 to C20. The gray arrow represents the scenario in which the Loess Plateau (LP) changes from C25 to C25 + D, then to C20, and finally to C20 + D.

example, in the C25 scenario (cropland with slopes >25° is converted to forest or grassland), the population experiencing grain shortages in the Yunnan-Guizhou Plateau in 2019 was projected to reach 6.29–6.91 million, calling for an additional 2.52–2.76 million tons of grain to be supplied to avoid grain shortages (Figure 4d). The GSSI of all scenarios in the Sichuan Basin (except C20) will exceed 1.0 from 2015 to 2030 (Figure 4b). Only in the C20 scenario did the GSSI drop significantly over time, but it was still projected to exceed 0.95 from 2015 to 2030 (Figure 4b). The GSSI of all scenarios on the Loess Plateau gradually reached 0.9 in the following years. In contrast to the pattern observed for the Yunnan-Guizhou Plateau and Sichuan Basin, cropland conversion scenarios for the Loess Plateau did not seem to lead to an inflection point for the GSSI (Figure 4c). Moreover, the GSSI value for the C25 + D (cropland with slopes >25° is converted to forest or grassland in conjunction with check dam construction) and C20 + D scenarios gradually became higher than that of the NC scenario. The numerous check dams on the Loess Plateau have intercepted 8.5 billion tons of sediment and formed 927.6 km^2 of high-quality cropland (CMWR, 2013). The continuous construction of check dams showed a positive effect on increasing grain output (Wang et al., 2011; Note S4 and Figure S6 in Supporting Information S1) and significantly increased the rate of GSSI increase over time (Shi et al., 2020). Converting cropland to forest or grassland in the Loess Plateau requires only the provision of grain at the early stages of GGP-2, starting with an annual supplement of 0.89–1.37 million tons in 2016 (Figure 4f) that is followed by a gradual rise to self-sufficiency (Figure 4c).

3.3. Trade-Offs Between Grain and Green

In the actual situation, 30,958 km^2 of slope cropland had been converted by 2019, resulting in 18.26 million people being exposed to grain risk (Methods S1 in Supporting Information S1). Under the NC scenario, the population experiencing grain shortages dropped significantly to 1.55 million in 2019. However, compared with the cropland conversion scenarios, the NC scenario would directly reduce the vegetation restoration area by 16,559–37,325 km^2. We find that all cropland conversion scenarios are better than the actual situation and the NC scenario when fully taking into account the vegetation restoration area and the population experiencing grain shortages (Figure 5). When we establish the optimal cropland conversion situation (i.e., Yunnan-Guizhou

Plateau: C25; Sichuan Basin: C20; Loess Plateau: C20 + D; Figure 5), the vegetation restoration area was 11% less than the actual situation. However, the population experiencing grain shortages in our study regions would be only 6.29–8.90 million (51–66% lower than the actual situation). Moreover, under this optimal design scenario, all three regions would gradually become self-sufficient in grain by 2030 (Figure 4).

4. Discussion

4.1. Grain Self-Sufficiency in Marginal Mountainous Areas

It is commonly believed that trade can solve the problem of inter-regional grain shortage. But we still need to pay more attention to regional grain self-sufficiency. Regional grain self-sufficiency can minimize the impact of adverse emergencies (Li et al., 2021), such as the supply chain disruption caused by the recent COVID-19 epidemic and grain production decline in main grain producing areas caused by extreme weather events (Iizumi et al., 2014). Over-reliance on regional grain trade may lead to insufficient regional grain supply. Furthermore, due to underdeveloped transportation and trade networks in the mountainous areas (Figure S7 in Supporting Information S1), coupled with the low consumption and purchasing power (Figure 3), farmers tend to grow grain to meet their own grain needs rather than buying grain (Zhan, 2017). Finally, traditional cultivation culture and government publicity have led Chinese farmers to have a deep-rooted ideology of smallholder and are very concerned about grain self-sufficiency (Qiao, 2013; Zhang & Cheng, 2016).

On the basis of ensuring regional grain self-sufficiency, it is necessary to optimize vegetation strategies to increase vegetation restoration area. The difference in the optimal strategies for the three key regions is mainly due to the different slope cropland characteristics (Figure 2), the GSSI before GGP-2 (Figure 4), and the adopted measures to increase grain output (Note S4 in Supporting Information S1). For example, C20 may cause YGP to face grain security risks due to the higher area and total grain output of cropland with slope >20°. On the contrary, C20 has no significant negative effect on grain supply on the LP, because its area and grain output of cropland with slope >20° were significantly lower than those of YGP and SB. Furthermore, the threat of large-scale vegetation restoration on LP to grain supply has been minimized by the construction of check dams. SB has a high GSSI before GGP-2 (Figure 4), which makes it less sensitive to the risk of grain output reduction caused by C20. Therefore, the strategy of vegetation restoration should be adapted to local conditions.

4.2. Challenges of Vegetation Restoration in Mountainous Areas

Our results indicate that the current vegetation restoration strategies in China are not sufficiently optimized, with insufficient vegetation restoration in one region and excessive vegetation restoration in another region. Insufficient vegetation restoration will retain too much low productivity steep slope cropland, leading farmers to fall into the vicious circle known as the "poverty trap" (Figure 6), in which steep slope farming leads to poverty and poverty intensifies steep slope farming (Barbier, 2010; Cao et al., 2009b, 2021; Note S5 in Supporting

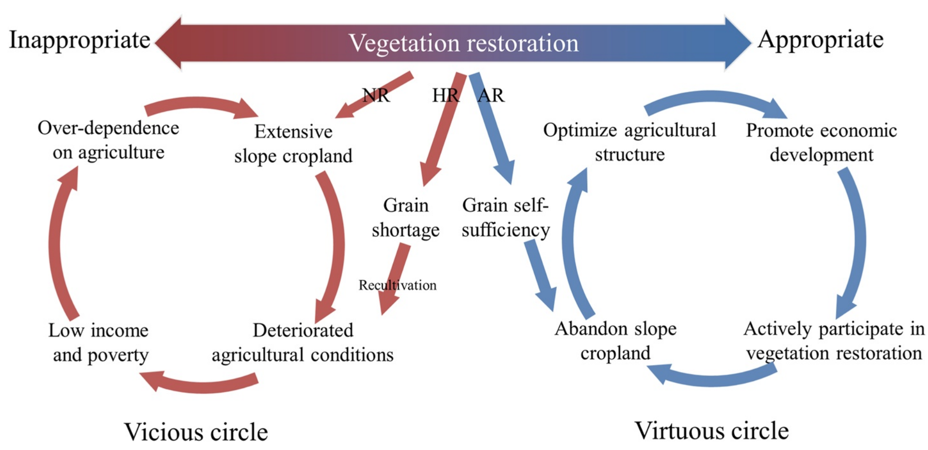

Figure 6. Virtuous and vicious circles caused by appropriate/inappropriate vegetation restoration. NR, no restoration; HR, higher-than-expected restoration; AR, appropriate restoration.

Information S1). Vegetation restoration in the mountainous areas of China will not affect national food security, because the restored steep slope cropland usually has a low grain yield (Kuang et al., 2021). However, the reduction in grain production caused by excessive vegetation restoration will inevitably threaten the survival and development of farmers in the mountainous areas, which are characterized by poor, less educated, and aging (Chen et al., 2015; NFGA, 2020). A large number of household surveys on GGP (including GGP-1 and GGP-2) showed that our study regions have the highest density of poor farmers with 86% of them with less than junior high school education (Note S6 and Table S4 in Supporting Information S1). Farmers in the mountainous areas, especially the poorest ones, rely heavily on slope cropland to achieve self-sufficiency. These people are the main targets of the UN no poverty goal (SDG 1) and are also the group most vulnerable to the negative effects of vegetation restoration programs (Von Braun & Gatzweiler, 2014). When there is a grain subsidy, they can continue to maintain vegetation restoration. However, once the grain subsidy stops, the vegetation restoration programs increase the survival risk of farmers, and the restored land (i.e., the land that has been converted from cropland to forest or grassland) faces the risk of recultivation (Cao et al., 2009b; Chen et al., 2009; Uchida et al., 2005; Note S6 and Figure S8 in Supporting Information S1). Household surveys indicate that 11.8–60.0% of the farmers have recultivated or shown the willingness to recultivate on restored land to meet the demand for grain and maintain their livelihood (Table S4 in Supporting Information S1). Once vegetation restoration programs threaten the livelihood and diminish the benefits of local farmers, farmers tend to recultivate the restored land (Cao et al., 2009b; Uchida et al., 2005). More importantly, due to the completion of the programs or the cessation of subsidies, farmers will not again choose to convert cropland to forests or grasslands (Cao et al., 2021; Chen et al., 2009). Thus, the damage to vegetation restoration caused by this recultivation of restored land is almost irreversible, resulting in the destruction of decades of vegetation restoration achievements and forcing farmers to fall back into the poverty trap (Cao et al., 2009b; Uchida et al., 2005; Figure 6).

In contrast, we find that the optimized design scenario can significantly reduce the risk of grain shortages while maintaining sustainable vegetation restoration. A study of 276 households on the Loess Plateau showed that when vegetation restoration programs do not affect grain self-sufficiency, farmers are unwilling to cultivate steep slopes or to employ recultivation on restored land due to the greater distance costs and lower grain yields (Wu et al., 2021). The abandonment of large swathes of low-quality cropland optimizes the agricultural structure, promotes the transfer of labor, and frees farmers from heavy and inefficient labor (NFGA, 2020). The mode of production in rural areas has changed from a small-scale peasant economy to a market economy, further promoting economic development in mountainous areas. When people in mountainous areas observe positive changes in the ecological environment and achieve tangible improvements in production and living conditions, they will proactively maintain and enhance the existing achievements resulting from vegetation restoration (Cao et al., 2009b; NFGA, 2020). This will eventually lead to a virtuous circle involving grain self-sufficiency, ecological restoration, and economic development (Figure 6).

4.3. Policy Suggestions and Implications

To improve the ecological environment and promote economic development in mountainous areas, the Chinese government has made enormous efforts to restore vegetation, and forest coverage has almost doubled from 12% in 1973 to 23% in 2018 (Bryan et al., 2018; Cao et al., 2021; Wang et al., 2021). Although the vegetation restoration programs that are still in progress may make China even greener, our results suggest that the current vegetation restoration strategies in the mountainous areas of China are not sufficiently optimized, which may threaten the livelihood of farmers and in turn affect the sustainability of vegetation restoration in the long run. Therefore, appropriate vegetation restoration strategies and multiple policies to increase grain production should be implemented to more reasonably and effectively achieve a win-win situation of grain and green.

First, the standards for vegetation restoration should be formulated and coordinated in accordance with local conditions (Lyu & Xu, 2020; Xu et al., 2006). The impact of vegetation restoration on grain supply varies from one region to another, and vegetation restoration solutions must be carefully tailored to the characteristics of slope cropland distribution, grain yield, and other ecological conditions in different regions (Feng et al., 2005). For regions with insufficient grain and a large proportion of steep slope cropland, the central government should provide more grain and financial assistance to ensure a stable regional grain supply, meeting the minimum requirements for cropland conversion. However, for regions with a low percentage of grain production on slope cropland or with sufficient grain production, we suggest that cropland with slopes >20° can be further converted into grassland or forest to better achieve the goals of soil and water conservation and carbon sequestration (Shi et al., 2020).

Second, cropland should be used more efficiently to increase grain yield. An increase in grain yield is a prerequisite for grain self-sufficiency (Niu et al., 2021). Our results indicate that the regional grain self-sufficiency rate has decreased after the implementation of two GGP phases (Figure 4), suggesting that these regions have not yet reached the stage of synergetic development of green and grain. We propose adherence to a strategy of sustainable cropland use and the innovative application of agricultural technology to increase cropland productivity. Such a strategy will include agricultural supply-side structural reforms to enhance the grain production capacity, improve grain circulation, optimize grain supply structure, and develop grain industry economics (Lyu & Xu, 2020). Then, related measures to increase grain yield (e.g., construction of check dams and terracing) should be undertaken according to local conditions to increase grain productivity (Shi et al., 2020). Through the implementation of the above strategies, more marginal cropland can be restored and more grain can be produced with less cropland, thereby promoting the synergetic development of grain and green.

Finally, poverty alleviation relocation is the fundamental solution to sustainable vegetation restoration in mountainous areas in the future (Zhao et al., 2021). The Chinese government needs to actively promote poverty alleviation relocation and accelerate the process of urbanization so that farmers in mountainous areas can leave the steep slope cropland with fragile ecosystems, low production potential, and inconvenient transportation and trade (Wang & Li, 2019). Once farmers' livelihoods are decoupled from slope cropland, it will be possible to achieve the sustainable development of vegetation restoration.

To achieve the Paris Agreement's goal of limiting global warming to 2°C or less, vegetation restoration has been considered a cost-effective and easily available option to mitigate climate change (Doelman et al., 2020). Global leaf area has increased by 5.4 million km^2 during the 2000–2017 period, largely due to the implementation of vegetation restoration programs worldwide (Chen et al., 2019). Target areas for vegetation restoration are often slope cropland in mountainous areas, where large-scale vegetation restoration involves a multitude of issues, such as grain supply, economic development, and ecological restoration (Rasul & Hussain, 2015; Zhang et al., 2020). As the largest-ever ecological restoration programs in the world, GGP was originally carried out to restore the degraded ecological environment in China's mountainous areas. The implementation of the GGP has brought numerous benefits to China and the world by solving a series of environmental problems and socio-economic challenges (Chen et al., 2015; Deng et al., 2017; Liu et al., 2008). Like China, many countries are engaged in mitigating climate change, improving environmental sustainability, and promoting quality of life through vegetation restoration. At the United Nations Climate Summit in 2014, many developing countries pledged to restore land to forest and grassland, and in total, parties committed to restoring vegetation on a staggering 350 million hectares by 2030 (Suding et al., 2015). To these countries with ambitious targets, our research demonstrates how vegetation restoration programs have worked in the past and provides a reference for determining potential future trajectories and achieving green and grain sustainability.

4.4. Limitations and Uncertainties

Our study does not distinguish cropland into different crop types, which is limited by the available cropland data set (Teluguntla et al., 2018). This further leads to the fact that the cropland data set may contain some nongrain crops. However, considering that the target of vegetation restoration is steep cropland with slope >15° or higher, such cropland will not be given priority to planting cash crops because of lower yields and higher production costs (Uchida et al., 2005). Therefore, the impact of a small proportion of nongrain crops in cropland data set on the results of vegetation restoration scenarios is likely very small. Although we use three widely used models for grain yield prediction to reduce errors. Grain yield may have been affected by many factors such as human activities (e.g., agricultural technology improvement) and climate change, which may cause some uncertainties. More detailed cropland data sets and grain yield prediction models are needed in future to obtain more accurate predictions. Finally, policies toward targeted poverty alleviation, poverty alleviation relocation, and urbanization may affect the framework of a virtuous or vicious circle in mountainous areas. But currently, there is a lack of data to decouple their intricate relationships. Future work to examine the impact of policies such as targeted poverty alleviation on the trade-offs between grain and green is needed.

5. Conclusions

In this study, we combined spatial statistics and scenario analysis to explore the optimal solution to the trade-offs between green and grain in mountainous areas of China. We found that there is still extensive steep slope cropland in China, mainly concentrated in the Loess Plateau, Sichuan Basin, and Yunnan-Guizhou Plateau. Farmers in these mountainous areas rely heavily on slope cropland and the grain it supplies. Particularly, the degree of reliance deepens with the aggravation of poverty. As a result, these mountainous areas are vulnerable to a poverty trap, in which steep slope farming leads to poverty and poverty intensifies steep slope farming. The large-scale vegetation restoration being implemented may aggravate this phenomenon, which may threaten the survival and development of the local farmers and in turn destroy existing vegetation restoration achievements. By simulating different vegetation restoration scenarios, we found that due to the different slope cropland characteristics, the GSSI before GGP-2, and the adopted measures to increase grain output, the impact of vegetation restoration on grain supply varies from region to region. In addition, we also found that the current vegetation restoration strategy can be further optimized to reduce the population suffering from grain shortages from 18.26 million to 6.29–8.9 million. To achieve a win-win situation of grain and green, we suggest that policy makers should adopt vegetation restoration strategies in accordance with local conditions and implement multiple policies to increase grain production while promoting the decoupling of farmers' livelihood from slope cropland.

Data Availability Statement

The following data sets were used in this study: China Cropland Extent-Product with a resolution of 30 m was obtained from Global Food Security-support Analysis Data (GFSAD; https://croplands.org/downloadLPDAAC). Population, economic, and grain output data were obtained from the National Statistical Yearbook (http://www.stats.gov.cn/english/Statisticaldata/AnnualData/). Household survey data were obtained from China Family Panel Studies (CFPS; http://www.isss.pku.edu.cn/cfps/en/index.htm?CSRFT=G32B-2O88-WZXV-SEHV-G6NJ-X9WH-UDPV-C5PE).

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