Spatiotemporal patterns of vegetation conversion under the Grain for Green Program in southwest China

Haiwei Zhao\textsuperscript{1,2} | Ruidong Wu\textsuperscript{1,2} | Feiling Yang\textsuperscript{1,2} | Jinming Hu\textsuperscript{1,2} | Junjun Wang\textsuperscript{1,2} | Yang Guo\textsuperscript{1,2} | Zhixue Feng\textsuperscript{1,2} | Chen Zhang\textsuperscript{1,2} | Yiting Wang\textsuperscript{1,2} | Jian Zhou\textsuperscript{1,2}

\textsuperscript{1}Conservation Biogeography Research Group, Institute of International Rivers and Eco-security, Yunnan University, Kunming, China
\textsuperscript{2}Yunnan Key Laboratory of International Rivers and Transboundary Eco-security, Yunnan University, Kunming, China

Correspondence
Ruidong Wu, Institute of International Rivers and Eco-security, Yunnan University, 2 North Green Lake Road, Kunming 650091, Yunnan, China.
Email: rdwu@ynu.edu.cn

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Abstract
China’s Grain for Green Program (GGP) is the largest reforestation program in the world. Previous studies lacked targeted assessments regarding its effectiveness in vegetation conversion. Using the time series of Vegetation Continuous Fields in southwest China, we derived the spatiotemporal variations in total vegetation cover, short vegetation (SV) cover and tree canopy (TC) cover during the period from 2000 to 2016. By conducting residual trend analyses independently on the SV and TC cover time series, the trends in human-induced SV cover (SV\textsubscript{H}) and TC cover (TC\textsubscript{H}) were detected. Then, we performed overlay analyses to derive the human-induced SV–TC conversion in cropland. The study found that the SV in southwest China showed a net browning trend whereas the TC presented a net greening trend. Approximately 69.5\% of the pixels with a significant browning trend in SV\textsubscript{H} showed a significant greening trend in TC\textsubscript{H}. Furthermore, 50.6\% of the human-induced SV–TC conversion in southwest China occurred in cropland, and the proportion was even larger for the eastern provinces. Our study provides a targeted evaluation of the performance of the GGP and highlights that the implementation of the GGP has caused widespread SV–TC conversion that potentially mitigates global climate change.

KEYWORDS
ecological restoration program, reforestation, residual trend analysis, restoration effectiveness, vegetation trend

1 | INTRODUCTION

Land degradation has become a global issue (Menz et al., 2013). Degraded hotspots cover approximately 29\% of the total land on Earth, affecting at least 3.2 billion people (Le et al., 2016). The losses of worldwide ecosystem services owning to land degradation have been estimated to be between 4.3 and 20.2 trillion $/year (Costanza et al., 2014). In response, many ecological restoration programs (ERPs) have been implemented globally to halt the degradation trend and advance a degradation-neutral planet (Jones et al., 2018). Ongoing monitoring and
quantitative evaluations of the outcomes of ERPs are essential to guide their adaptive governance and achieve the United Nation’s Sustainable Development Goal of reversing land degradation (Wu, Possingham, et al., 2019; Wu, Wang, et al., 2019).

China has launched a series of large-scale ERPs since the end of the twentieth century to address sustainability emergencies (Bryan et al., 2018; Zhao et al., 2020). Initiated in the year of 1999, the Grain for Green Program (GGP) is the largest reforestation program and payment for ecosystem services scheme around the world, affecting 124 million people and 32 million households in China (Ahrends et al., 2017; Delang & Yuan, 2015). The main objectives of the GGP are to reduce soil erosion, improve tree cover and alleviate poverty by converting cropland on slopes to forests and subsidizing farmers (Bryan et al., 2018). As of 2017, China had invested a total of 372.57 billion yuan in the GGP and had afforested 27.83 million ha of land, including at least 10.21 million ha of retired cropland (“退耕还林” in Chinese) (National Forestry and Grassland Administration of China, 2018). However, the effectiveness of the GGP in restoring vegetation has long been disputed because targeted and independent evaluations of the outcomes have been lacking (Cao et al., 2009; Cao et al., 2011; Wang et al., 2020).

Previous studies generally assessed the effectiveness of the GGP by analyzing trends in the vegetation index or by detecting transitions among discrete land cover (LC) types (e.g., Tong et al., 2017; Zhou et al., 2012). However, the vegetation index merely measures the photosynthetically active vegetation cover and cannot distinguish between crops and tree canopies (Brandt et al., 2017). Zhao et al. (2020) found the peak growing season Normalized Difference Vegetation Index (NDVI) in the eastern part of southwest China presented a significant increasing trend during 1999–2015, but whether it indicated the gains of forest or other vegetation could not be determined. In addition, discrete LC mapping does not realistically reflect vegetation mosaics within a grid cell, and subtle LC changes and vegetation variations within a cover type are obscured (Defries et al., 2000). As a result, the true impacts of the GGP, that is, the conversion from crops to forests, can be concealed to a large degree.

Vegetation Continuous Fields (VCF) depict vegetation attributes by the percentage of each pixel taken by a particular functional type, such as tree canopy (TC) or short vegetation (SV) (Carroll et al., 2010; Song et al., 2018). Since anthropogenic land-cover changes are generally characterized by high spatial heterogeneity and fragmentation, VCF characterization provides a more effective metric for detecting variations that could not be identified by comparing consecutive discrete classifications (Hansen & DeFries, 2004). However, to our knowledge, few studies have provided a targeted evaluation of the effectiveness of the GGP in vegetation conversion by applying the combination of fractional SV cover and TC cover.

By analyzing residual VCF time series trends, including the time series of TC cover and the time series of SV cover, the present study intended to answer the following questions. How effective has the GGP been at restoring vegetation? Has the greening vegetation trend in southwest China mainly been caused by anthropogenic forest gain? Has large-scale vegetation conversion occurred following the implementation of the GGP? The combined employment of fractional TC cover and SV cover presents a targeted assessment of the effectiveness of the GGP in vegetation conversion. Answering these questions is essential to inform policy makers regarding the outcomes of the GGP and promote the sound planning and implementation of ERPs in the future. This study also provides a typical model for considering vegetation functional types when evaluating the outcomes of ERPs that is applicable to other parts of the world.

2 STUDY AREA

Southwest China occupies a total area of approximately $2.33 \times 10^6$ km$^2$ ($21^\circ–37^\circ$N, $84^\circ–112^\circ$E), which is approximately equivalent to one-fourth of China’s territory and is composed of seven provinces (Yunnan, Guizhou, Sichuan, Guangxi, Chongqing, southern Qinghai, and east-central Xizang). The boundary is drawn based on their affiliate counties that belong to southwest China. The terrain is dominated by mountains and plateaus where the altitude rises steadily from the southeast to the northwest. Accordingly, the annual precipitation changes gradually from >1500 mm to no more than 50 mm, whereas the mean temperature from >20°C to less than 0°C (Zhao et al., 2019). The east-central part of southwest China is located in the forest biome, whereas the western part falls primarily within the alpine meadow/shrubland biome and alpine steppe biome (Ni, 2000).

Southwest China, one of the largest karst regions on Earth, is susceptible to desertification as human disturbance intensifies. The total area of rocky desertification has exceeded 100,000 km$^2$ in southwest China, making this area suffer natural disasters regularly, such as droughts, landslides, floods, and subsidence (Jiang et al., 2014). In addition, southwest China lies in the upper reaches of several great rivers involving the Yangtze River, the Pearl River, and some international rivers. Triggered by the devastating 1998 Yangtze River floods, the GGP was piloted in Sichuan in the following year and was expanded to Chongqing, Guizhou, Yunnan and Qinghai in 2000. In 2002, the
GGP was officially implemented across the seven provinces in southwest China (Bryan et al., 2018).

3 | DATA

3.1 | VCF data

We used the National Aeronautics and Space Administration Making Earth System Data Records for Use in Research Environments VCF products (Song et al., 2018). The products were maps of annual fractional vegetation cover in three layers: SV cover, TC cover, and bare ground cover. The yearly layers were mapped during the local peak growing season at a 5600 m spatial resolution. For southwest China, the local peak growing season generally refers to August in each year (Piao et al., 2003). The time series of SV cover and TC cover from 2001 to 2016 were derived from the VCF products. For each year, we generated a layer of total vegetation (TV) cover by summing the fractional covers of SV and TC. The three time series, that is, the time series of SV cover, the time series of TC cover and the time series of TV cover, were used in the study. For each time series, we calculated the average cover for the period from 2001 to 2016, based on which the sparsely vegetated areas were defined (pixel-based average cover <5%). Since optical remote sensing data are strongly affected by ground conditions in sparsely vegetated areas and thus cannot accurately indicate vegetation status, these areas (i.e., sparsely SV-vegetated areas, sparsely TC-vegetated areas, and sparsely TV-vegetated areas) were eliminated for further analyses in the corresponding time series (Fang et al., 2004).

3.2 | Climate data

The datasets of monthly mean temperature and monthly precipitation for the years 2001–2016 were derived from 935 meteorological stations in China, which were obtained from obtained from National Meteorological Information Center of China (http://data.cma.cn). Using the thin plate smoothing spline method with ANUSPLIN software, the monthly data were interpolated to raster layers at a 1-km resolution (Hutchinson & Xu, 2013). Then we clipped the interpolated climate layers for southwest China and resampled them to the resolution of VCF data.

The growth of plants is greatly affected by the simultaneous rises of temperature and precipitation during the growing season, which represents the characteristic vegetation-climate relationship of China (Fang et al., 2004). Previous studies have revealed the reaction of plant growth falls behind increases in temperature and precipitation (Herrmann et al., 2005; Piao et al., 2003). To properly simulate the relationship between vegetation and climate, 15 metrics of mean temperature and 15 metrics of cumulative precipitation over the growing season (from April to August) were calculated for each year with different durations and time lags (Table S1).

3.3 | LC data

LC data for the year 2000, produced by the LC project of the European Space Agency (ESA) Climate Change Initiative (CCI) at a 300 m resolution, were downloaded from the CCI-LC database (http://maps.elie.ucl.ac.be/CCI/viewer/index.html). The typology of the product was defined based on the LC Classification System (LCCS) established by the United Nations Food and Agriculture Organization (Di Gregorio, 2005). The cropland classes of southwest China, including rainfed cropland, irrigated cropland, mosaic cropland (>50%)/natural vegetation (<50%) and mosaic natural vegetation (>50%)/cropland (<50%), were extracted from the LC product (Figure S1).

3.4 | Statistical data of the GGP

The afforested areas in retired cropland for the seven provinces under the implementation of the GGP from 2001 to 2016 were compiled from the China Forestry Statistical Yearbook (National Forestry and Grassland Administration of China, 2018). The statistics for each province were summed for the whole province, but southwest China covers 34.1 and 60.2% of Qinghai and Xizang, respectively.

4 | METHODS

The methodological framework used in this study is illustrated in Figure S2.

4.1 | Trend analyses

To disclose and compare vegetation changes in the three time series mentioned above, linear regressions between corresponding vegetation covers and year were applied at the per-pixel level. Taking the time series of SV cover as an example, the per-pixel regression slope was determined for each pixel using the ordinary least squares (OLS) method, indicating the magnitude and direction of SV cover trend. The pixel-based slope was calculated with Equation (1).
where $n$ equals 16 because the time series of SV cover spanned 16 years; $i$ is the year order, from 1 to 16; and $C_i$ indicates the SV cover for year $i$. We then computed the per-pixel Pearson correlation coefficients, that is, $r$ values, between SV cover and time. Pixels with a significant SV increasing trend ($r > .426$) or a significant SV decreasing trend ($r < -.426$) at the 95% confidence level were detected (Fensholt et al., 2009). With these procedures, we produced two significant trend layers, a significant greening (increasing) trend layer (GTL) and a significant browning (decreasing) trend layer (TBL), for each time series. In addition, the temporal cover trends for SV, TC, and TV on a spatial average basis were also determined by the OLS method. The significance of the regional vegetation trends was checked at the 95% confidence level.

4.2 Residual trend analyses of SV cover and TC cover

Residual trend analysis represents a robust technique for separating human- and climate-induced vegetation variations (Evans & Geerken, 2004; Liu et al., 2018; Wu et al., 2014). In this study, we used residual trend analysis to analyze the time series of SV cover and the time series of TC cover at the pixel level, to derive anthropogenic SV cover and TC cover trends, respectively.

Taking the residual trend analysis of SV cover time series as an example, first, we built a pixel-based linear regression model between SV cover and climate variables. To select the optimal climate variables for the model, we performed Pearson correlation analyses between SV cover and 15 combinations of mean temperature and cumulative precipitation. The temperature variable with the highest absolute $r$ value (Figure S3) and the precipitation variable with the highest absolute $r$ value (Figure S4) were selected as the optimal climate explanatory variables for the model. The per-pixel SV cover climate regression model was determined with Equation (2) (Tong et al., 2017).

$$SV_{m,n} = a_0 \times T_{\text{optimal},m,n} + b_0 \times P_{\text{optimal},m,n} + c_0$$ (2)

where $SV_{m,n}$ is the SV cover for pixel $m$ in year $n$; $T_{\text{optimal},m,n}$ is the optimal mean temperature for pixel $m$ in year $n$; $P_{\text{optimal},m,n}$ is the optimal cumulative precipitation for pixel $m$ in year $n$; $a_0$ and $b_0$ represent the corresponding regression coefficients for the explanatory variables of mean temperature and cumulative precipitation, respectively; $c_0$ indicates the constant value. We checked the statistical significance of the models at the 95% confidence level by conducting $F$ test on a per-pixel basis. In the following analyses, SV cover climate residuals were calculated only for the pixels with significant SV cover climate models (Figure S5).

Then, for each year, we used the model to predict the climate-induced SV cover ($SV_C$) for each pixel with optimal mean temperature and cumulative precipitation. The human-induced SV cover ($SV_H$) was calculated by pixel as the residual between the observed SV cover ($SV_O$) and $SV_C$, that is, $SV_H = SV_O - SV_C$. For pixels that the SV cover climate models were statistically insignificant (Figure S5), we assumed that $SV_O$ was entirely brought about by human activities, for example, crop cultivation in wastelands or permanent SV clearance in the urbanization process (Song et al., 2018). Then, using the methods presented in Section 4.1, we determined the temporal trends in $SV_H$ during 2001–2016 on a per-pixel basis and identified the pixels with a significant $SV_H$ trend at the 95% confidence level. With these procedures, two significant trend layers for $SV_H$, that is, the $SV_H$ GTL and $SV_H$ BTL, were generated.

Following the steps above, we conducted a residual trend analysis on the time series of TC cover. The assembled temperature variable and assembled precipitation variable that were introduced to the pixel-based TC cover climate regression model are illustrated in Figures S6 and S7, respectively. The pixels with significant TC cover climate models are presented in Figure S8. Finally, the GTL of human-induced TC cover ($TC_H$) and BTL of $TC_H$ were generated. To detect human-induced vegetation change at the regional scale, the temporal trends in $SV_H$ and $TC_H$ were analyzed on a spatial average basis, and their significance was verified at the 95% confidence level.

4.3 Overlay analyses

To determine human-induced SV–TC conversion from 2001 to 2016, we overlaid the $SV_H$ BTL and $TC_H$ GTL to produce a human-induced SV–TC conversion layer. Then, we overlaid the human-induced SV–TC conversion layer with the cropland layer of 2000 to identify the human-induced SV–TC conversion occurring in cropland. The GGP, also known as the Conversion of Cropland to Forest Program or the Sloping Land Conversion Program, mainly aims to convert cropland to forestland by afforestation (Gutiérrez Rodríguez et al., 2016). Therefore, the human-induced SV–TC conversion in cropland could be
FIGURE 1  Spatiotemporal patterns of the total vegetation (TV) cover trend (a), short vegetation (SV) cover trend (b), and tree canopy (TC) cover trend (c) in southwest China
considered the proxy for the effectiveness of the GGP in forest restoration.

5 | RESULTS

5.1 | Spatiotemporal patterns of the vegetation trends

From 2001 to 2016, approximately 24.0% of the TV presented a significant increasing trend \((p < .05)\), mainly spread in the southeastern and northwestern parts of southwest China. Approximately 2.8% of the TV showed a significant browning trend \((p < .05)\), principally distributed in south-central Xizang as well as in the vicinities of capital cities such as Chengdu and Kunming. Approximately 73.2% of the TV remained stable, mainly spread in the central part of southwest China (Figure 1(a); Table S2). The mean TV cover in southwest China presented a significant upward trend of 0.127% year\(^{-1}\) \((p = .014)\) (Figure S9).

Approximately 17.8% of SV showed a significant negative trend \((p < .05)\), mainly distributed in the eastern part of southwest China such as eastern Chongqing, northern Guizhou, northeastern Sichuan and northeastern Yunnan. SV with a significant greening trend \((p < .05)\) was primarily spread in Qinghai and Xizang and accounted for 6.5%. Approximately 75.7% of SV presented no significant trend (Figure 1(b); Table S3). At the scale of southwest China, the mean SV cover decreased significantly by \(-0.172\%\) year\(^{-1}\) \((p = .027)\) (Figure S9).
TC with a significant greening trend ($p < .05$) was mainly distributed in the eastern part of southwest China, corresponding to the areas with significant browning trends in SV and accounting for 35.7%. Only 1.2% of TC showed a significant browning trend ($p < .05$), and the area was sparsely scattered throughout southwest China. Approximately 63.1% of TC showed no significant trend (Figure 1(c); Table S4). On a spatial average basis, the TC cover in southwest China increased significantly at the rate of 0.483% ($p < .001$) (Figure S9).

5.2 Spatiotemporal patterns of the $SV_H$ trends and $TC_H$ trends

Pixels representing a significant negative trend ($p < .05$) in $SV_H$ were primarily spread in the eastern part of southwest China, such as eastern Chongqing, northern Guizhou and northeastern Sichuan, accounting for 13.5% of the SV-vegetated pixels. SV that was significantly improved by human activities was mainly scattered in Qinghai and Xizang, constituting only 3.7%. Up to 82.8% of the $SV_H$ in southwest China remained stable (Figure 2(a); Table S5). At the scale of southwest China, the mean $SV_H$ cover decreased significantly, by 0.134% year$^{-1}$ ($p = .020$) (Figure 3).

**FIGURE 3** Temporal trends for the mean human-induced SV ($SV_{HI}$) cover and mean human-induced TC ($TC_{HI}$) cover in southwest China. [Correction added on 24 December 2021, after first online publication: Figure 3 caption was revised.]

**FIGURE 4** Spatial patterns of human-induced short vegetation (SV)–tree canopy (TC) conversion in southwest China
FIGURE 5  Spatial patterns of human-induced short vegetation (SV)–tree canopy (TC) conversion in cropland in southwest China

FIGURE 6  Pixel statistics of the human-induced SV (SVH) browning trend, human-induced short vegetation (SV)–tree canopy (TC) conversion and human-induced SV–TC conversion in cropland for the seven provinces of southwest China
Approximately 26.1% of the TC-vegetated areas were significantly improved by human activities ($p < .05$). These areas were primarily distributed in the eastern part of southwest China, which corresponded to the areas where $SV_{H}$ presented a significant browning trend. Only 1.0% of the TC-vegetated areas were negatively affected by human activities ($p < .05$). Around 72.9% of the TC-vegetated areas were not significantly affected by human activities (Figure 2(b); Table S6). Overall, the mean $TC_{H}$ cover in southwest China showed a significant increasing trend of 0.324% year$^{-1}$ ($p < .001$) (Figure 3).

### 5.3 Human-induced SV–TC conversion in southwest China

From 2001 to 2016, human-induced SV–TC conversion mainly occurred in the eastern part of southwest China (Figure 4). Across southwest China, approximately 69.5% of the pixels with a significant decreasing trend in $SV_{H}$ showed a significant increasing trend in $TC_{H}$. The proportion was even larger for the eastern provinces, such as Chongqing (87.7%) and Guizhou (87.1%). In contrast, less than 10% of the pixels with a significant decreasing trend in $SV_{H}$ presented a significant increasing trend in $TC_{H}$ in the western provinces, such as Qinghai (0%) and Xizang (6.4%) (Figure 6; Table S7).

Approximately 50.6% of human-induced SV–TC conversion in southwest China occurred in cropland (Figure 5; Table S7). The human-induced SV–TC conversion in cropland was heterogeneous among provinces (Figure 6). In Guizhou, 67.1% of the anthropogenic SV–TC conversion was detected in cropland, followed by Chongqing (60.5%). Only 6.8% of the conversion occurred in the cropland of Xizang (Figure 6; Table S7).

### 6 DISCUSSION

#### 6.1 The greening trend in southwest China

This study demonstrated the TV in southwest China presented a net greening trend from 2001 to 2016, which was in line with recent studies (Brandt et al., 2018; Chen et al., 2019; Tong et al., 2018). The net greening vegetation trend was driven by both climate and restoration efforts (Cai et al., 2014; Tong et al., 2017), though the annual rainfall and soil moisture were found to be declining by 8 and 5%, respectively during 1999–2012 (Brandt et al., 2018). A browning TV trend was detected in the vicinities of major cities that were attributed to rapid urbanization in southwest China during the period (Zhang & Seto, 2011). The local governments should balance vegetation recovery with socioeconomic development to achieve more synergies between them (Liu et al., 2019).

Further analyses of the spatiotemporal variations in the vegetation components demonstrated that the TC in southwest China presented a net greening trend, whereas the SV showed a net browning trend, indicating that the increase in TC cover determined the greening trend in southwest China. On the one hand, most of the marginal cropland in southwest China was converted to forest under the implementation of the GGP, especially in the eastern provinces (Figure 5; Tong et al., 2017). During the period from 2001 to 2016, more than 2.74 million ha of retired croplands were converted to forests in the seven provinces of southwest China (Figure S10). On the other hand, compared with forests, the SV was more susceptible to aridity suppression when southwest China experienced severe drought from 2009 to 2010 (Li et al., 2019). Analyses of the $SV_{C}$ and $TC_{C}$ trends also revealed that the SV was widely suppressed by climate in the east-central part of southwest China, whereas the TC generally improved, which supported the results of Li et al. (2018). The extensive SV greening on the Tibetan Plateau widely improved, which supported the results of Li et al. (2018). The extensive SV greening on the Tibetan Plateau was primarily driven by the climate (Figures S11 and S12). Furthermore, the growth of new plantations would compete for water and sunlight with understory vegetation and thus further inhibit the increase in SV cover (Cao et al., 2009). However, our study revealed that the SV on the Tibetan Plateau widely improved, which supported the results of Li et al. (2018). The extensive SV greening on the Tibetan Plateau was primarily driven by the climate (Figure S11; Lehnert et al., 2016). Nevertheless, the SV browning in south-central Xizang was induced by a combination of overgrazing and drought (Lehnert et al., 2016).

#### 6.2 The impacts of human activities on vegetation trends

Our study revealed that the spatial patterns of the $SV_{H}$ and $TC_{H}$ trends were comparable to those of the SV and TC trends, respectively, reflecting the strong effect of anthropogenic activities on the dynamics of vegetation in southwest China. Our results further demonstrated that human activities exerted more positive effects on TC than on SV because afforestation and reforestation programs were the fundamental mode of active restoration in China (Wu, Possingham, et al., 2019; Wu, Wang, et al., 2019). Many large-scale ERPs, such as the GGP, place relatively more emphasis on active tree planting and focus intensely on increasing forest cover (Hua et al., 2018; Xu, 2011). As a result, a total of 100.56 million ha of land was afforested or reforested in China by
2016 following the implementation of large-scale forestry ERPs (National Forestry and Grassland Administration of China, 2018). Southwest China has been one of the major targets of forest restoration efforts, and thus, more TC\textsubscript{14} increases were found in that region (Tong et al., 2018).

However, forest stands are overwhelmingly monocultures of nonnative species under the implementation of the GGP (Hua et al., 2016). In the background of TC greening, there has been a virtual net loss of native forests in some areas of southwest China (Hua et al., 2018). Compared with natural forests, plantations are less ecologically resilient and are more vulnerable to disturbances such as droughts, insects and diseases (Brandt et al., 2018). In addition, planted forests consume more water but sequester less carbon than natural forests (Yu et al., 2019). Moreover, the results of a recent large-scale subtropical forest experiment confirmed that tree species richness exerted a strong positive impact on tree productivity at the stand level, suggesting that mixed plantations of native species would achieve cobenefits in both active biodiversity management and higher levels of ecosystem services (Huang et al., 2018).

### 6.3 SV–TC conversion under the implementation of the GGP

Our study revealed that large-scale human-induced SV–TC conversion has emerged under the implementation of the GGP that potentially has socioecological impacts (Wu, Possingham, et al., 2019; Wu, Wang et al., 2019). It was estimated that the annual carbon sequestration of planted forests in China attributed to the GGP could counterweigh 1% of global carbon emissions (Deng et al., 2017). In addition, the conversion of cropland to forests increases soil organic carbon significantly up to a depth of 60 cm (Shi et al., 2013). SV–TC conversion also alters local albedo and energy budgets, which decreases the daytime land surface temperature by 1.1 ± 0.5°C and increases the nighttime temperature by 0.2 ± 0.5°C in China (Peng et al., 2014). However, due to the intense implementation of the program in some provinces, the grain supply was significantly reduced at the scale level (Feng et al., 2005). Nevertheless, the positive effects of the conversion will probably strengthen over time (Deng et al., 2014).

This study disclosed that the effectiveness of the GGP was heterogeneous among provinces, which was in line with regional- and national-scale studies (Lü et al., 2015; Wang et al., 2020). In southwest China, the SV–TC conversion in cropland primarily occurred in Guizhou and Chongqing, whereas hardly any conversion was detected in the western part, such as Xizang (Figure 5). On the one hand, the GGP was implemented unevenly among the provinces. For example, approximately 558,925 ha of cropland was converted to forest in Guizhou, whereas only 5537 ha of retired cropland in Xizang was afforested during the period from 2001 to 2016 (Figure S10). On the other hand, the outcomes of the GGP are strongly influenced by heterogeneity in the biophysical and socioeconomic conditions in southwest China (Lü et al., 2015). The western part of southwest China lies within the grassy biome with scarce precipitation. It is ineffective and even catastrophic to plant trees in grassy biomes (Veldman et al., 2015). The outmigrant population in Guizhou increased from 3.16 × 10\textsuperscript{5} in 2000 to 9.46 × 10\textsuperscript{5} in 2010; this change promoted the abandonment of cropland and reduced negative anthropogenic disturbances on forests, thus contributing to forest restoration (Cai et al., 2014). The different management levels of the restoration actions among the provinces could also have produced heterogeneous outcomes (Tong et al., 2017). Given the biophysical and socioeconomic factors, the implementation of the GGP must be tailored to local conditions (Cao et al., 2011). Moreover, mixed forests should be promoted over monocultures to achieve better biodiversity outcomes and stronger ecological resilience (Hua et al., 2016). In addition, native forest regrowth via natural regeneration on land freed up from agriculture should be incorporated in the GGP as a legitimate means of forest restoration (Hua et al., 2018). Last but not least, cropland retirement for afforestation and grain production must be well balanced to ensure food security in the long term (Chen et al., 2015).

### 6.4 The importance of adopting characteristic proxies in evaluating the effectiveness of the GGP

Assessing the outcomes of ERPs is often challenging due to incomplete project information, improper evaluation standards, and ever-changing baselines (Suding, 2011). Given these factors, previous studies generally adopted proxies of TV, such as the NDVI, to assess the outcomes of the GGP (Tong et al., 2017). To a certain degree, an increasing trend in TV can reflect the effectiveness of the GGP in promoting vegetation cover (Lü et al., 2015). However, there are some drawbacks regarding the metrics when deriving the true impacts of the GGP. The determined outcomes are essentially the effectiveness of multiple ERPs if other ERPs aimed at increasing vegetation cover are implemented in the study area. In addition,
the results were unable to reflect the dynamics of vegetation components and the SV–TC conversion caused by the implementation of the GGP.

The effectiveness of a restoration intervention has a broad sense, ranging from purely biophysical influences to ecological and socioeconomic effects, because an ERP generally has multiple goals (Meroni et al., 2017). When evaluating the effectiveness of a specific ERP, it is necessary to select and measure the characteristic attributes of the ERP, especially in areas where several restoration actions are being performed in parallel. Though other large-scale ERPs have been implemented in southwest China with the goal of improving vegetation cover, the GGP mainly targets the conversion of retired cropland to forest, which represents the primary characteristic for distinguishing it from other ERPs (Bryan et al., 2018). Therefore, it is appropriate to assess the performance of the GGP with the indicator of human-induced SV–TC conversion in cropland, which avoids the problems mentioned above. However, it should be noted that the effectiveness of the GGP indicated by this metric is conservative. Apart from converting retired cropland to forest, the goals of the GGP also involve planting trees and grasses on bare land (Deng et al., 2017). Since the VCF product used in this study contained only two vegetation layers, that is, the SV cover layer and the TC cover layer, we used the SV changes that occurred in the cropland class to portray the dynamics of crops, and this method might involve some uncertainties. In the future, more detailed VCF products containing fractional crop cover must be generated and applied to the monitoring and evaluation of the GGP.

7 | CONCLUSIONS

On the basis of VCF time series in southwest China, we conducted a targeted and independent assessment on the outcomes of the GGP regarding vegetation conversion. Our study found that the vegetation in southwest China widely improved during the period from 2001 to 2016. The large-scale vegetation greening was primarily contributed by the TC increase in the eastern part and the SV increase in the western part. Following the implementation of the GGP, large areas of SV were converted to TC by human activities in southwest China, more than half of which occurred in cropland. The proportion of anthropogenic SV–TC conversion in cropland was even larger for the eastern provinces, such as Guizhou and Chongqing. The widespread SV–TC conversion potentially exerted a significant impact on global climate change. This study provides targeted and quantitative evidence on the effectiveness of the GGP regarding vegetation conversion and can guide the adaptive governance and planning of this program in the future.

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CONFLICT OF INTEREST

The authors declare no potential conflicts of interest.

DATA AVAILABILITY STATEMENT

All data for this study are available as online supporting information.

ETHICS STATEMENT

All data were collected from online databases and literature following research ethics. No ethical approval was required for this study.

ORCID

Haiwei Zhao https://orcid.org/0000-0003-0259-3789  
Ruidong Wu https://orcid.org/0000-0002-9908-1802

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SUPPORTING INFORMATION
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