Distinguishing ecological outcomes of pathways in the Grain for Green Program in the subtropical areas of China

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Abstract

Effective forestation policies are urgently required across the globe under the initiative of the UN Decade on Ecosystem Restoration. Rather than simply planting trees, such initiatives involve complex components of societal and biophysical systems. However, the underlying pathways by which forestation influences ecological outcomes are not well understood, especially given the lack of a unified quantification framework. In this study, such a framework was developed to reveal the pathways by which reforestation programs influenced ecological outcomes by identifying the linkages among reforestation efforts, societal changes, land system changes and ecological outcomes. The framework was applied to the reforestation program of the Grain for Green Program (GFGP), to explore how the GFGP influenced vegetation dynamics and ecosystem functioning in Guizhou Province, China, through direct and indirect pathways. Two remote sensing based indicators, namely the enhanced vegetation index, derived from the Moderate Resolution Imaging Spectroradiometer, and gross primary production (GPP), obtained from the Orbiting Carbon Observatory-2 solar-induced chlorophyll fluorescence (SIF) fine-resolution dataset GOSIF, were combined with inventory data and land-use maps to detect changes in social and ecological outcomes. Using the structural equation model to apply the framework, the results showed that the GFGP positively contributed to the increasing greenness and GPP of the study area through the direct conservation pathway. Although implementation of the GFGP encouraged the rural outmigration and led to a decrease in the area of farmland, the GFGP showed negative indirect effects on greenness and GPP because of the difficulty of reforestation during land-use conversion from farmland to forest land. This study revealed divergent impacts of the reforestation program through multiple pathways, which could provide valuable information for other parts of the globe for more precise design of ecological restoration policies.

1. Introduction

Crisis narratives have spurred global efforts to explore restorative solutions to halt land degradation, conserve ecosystems and improve human well-being (UNCCD 2013, Conway et al. 2015, Bryan et al. 2018). Forestation (including afforestation and reforestation) has been proposed as an effective solution with the establishment of forests by direct human interventions such as planting and seeding (Meyfroidt and Lambin 2011, Bastin et al. 2019, Zeng et al. 2020). Although ambitious forestation initiatives have been undertaken worldwide, some failed to obtain net gains in terms of biodiversity, ecosystem function or human well-being (Heilmayr et al. 2020, Coleman et al. 2021). Therefore, huge gaps remain between high-level forestation initiatives and their implementation on the ground (Menz et al. 2013, Holl and Brancalion 2020).

Current forestation programs go beyond simply and rapidly planting trees because they involve multiple societal and biophysical components and have diverse effects on ecological and social systems (Wells et al. 2020, Zeng et al. 2020). As the global community embarks on the initiative of the UN Decade on Ecosystem Restoration in 2021, revealing how different
components interact with each other in the process of implementing forestation will improve our understanding of the costs and benefits and thus provide specific supporting for policy-makers (Strassburg et al 2019, UN 2019, Cai et al 2020).

Forest transition theory provides insights into how societal and biophysical changes link to forest dynamics, and can be used to explore complex processes in forestation programs. Forest transition refers to the phenomenon that a given region experiences a change in its net forest area from a decrease to an increase (Mather 1992). Forest transition can be caused by a mixture of factors and processes (Rudel et al 2005, Meyfroidt and Lambin 2009, Jadin et al 2016). Apart from forestation programs led by governments to supplement timber shortages or to prevent environmental degradation, forest transition can also occur because of socio-economic development and intensification of agriculture (Lambin and Meyfroidt 2010). For instance, in some tropical areas, vegetation can regenerate naturally after land has been abandoned because of transformation of farmers’ livelihoods from on-farm based activities to off-farm ones (Rudel et al 2005, Rudel 2009, Zhang et al 2017). Generally speaking, the initial view of forest transition only focused on forest area dynamics and did not capture the detailed characteristics of a given region, such as biomass density. Recent research has suggested that the shift in forest biomass density from sparser to denser should also be regarded as forest transition (Kauppi et al 2020, Le Noe et al 2020). In this way, linkages among societal changes, forest dynamics and ecosystem functioning are established, which could be used to acknowledge the role of forestation programs in mitigating climate change and combating land degradation. However, how to explore such linkages is still lacking in the existing literature.

China has been engaged in large forestation programs since the 1990s, with multiple implications for the design of appropriate policies (Delang and Yuan 2015, Bryan et al 2018). Although many studies have assessed the effects of these programs on outcomes, the complex linkages among vital components involved in the forestation programs have not been well quantified (Liu et al 2008, Yang et al 2018, Tong et al 2020). Here, we have developed a conceptual framework by applying the theory of forest transition to reveal the direct and indirect pathways by which the forestation program has influenced ecosystem outcomes through a case study in China. The operationalization of the framework is demonstrated using the structural equation model (SEM) approach, with a special focus on the Grain for Green Program (GFGP), one of the most ambitious reforestation programs in the world. In detail, the interactions among different components during implementation of the GFGP are quantified and the pathways through which human interventions affected landscape restoration are identified.

2. Materials and methods

2.1. Study area

Guizhou Province, a hotspot for significant biomass increases due to government-led forestation programs (Brandt et al 2018, Tong et al 2018, Wang et al 2019), was chosen as the study area. The study area is located at 24°30′ E–29°13′ E and 103°1′ N–109°30′ N with a total land area of 176 000 km² (figure 1). More than 90% of the study area is mountainous or hilly, with an average elevation of about 1104 m. The natural conditions of the study area are characterized to be vulnerable because more than 60% of the land is covered by the karst landform (a landscape based on soluble rocks), resulting in poor soil quality and low soil moisture (Qiu et al 2020). The population pressure and previous development have led to severe land degradation, called Karst Rocky Desertification (Wang et al 2004). Since the 1990s, the Chinese government has launched a series of programs to restore the degraded forest lands and to improve the well-being of the local human population in the study area.

2.2. Research framework

Based on forest transition theory (Lambin and Meyfroidt 2010, Kauppi et al 2020, Rudel et al 2020), the linkages among reforestation programs, societal changes, land system changes and ecological outcomes can be conceptualized, as shown in figure 2(a). The reforestation program in this study refers to the GFGP, which aims to address environmental issues by converting farmland into forest land (Delang and Yuan 2015), inevitably resulting in multiple changes (Zhang et al 2017). The impact pathways in the study area were hypothesized as shown in figure 2(b). In detail, the most direct impact is on the land system; subsequently, the social system will be impacted in both direct and indirect ways, in particular for rural residents. On one hand, farmers who rely on farmland may need to change their livelihood passively because some farmland will be converted to forest land. On the other hand, the subsidies offered through the program may encourage farmers to leave their on-farm job voluntarily. Both cases can lead to farmland decreasing and rural outmigration. However, it is not clear whether farmlands can be successfully converted into productive forest lands. This process can be divided into successive steps: farmland decreasing, forest land increasing, greening forest and enhancement of gross primary production (GPP). In addition, such a program has a direct impact on ecosystems through conservation pathways, such as halting logging and strengthening people’s awareness to protect forests.

In order to distinguish the effects generated by divergent pathways, we selected appropriate
indicators to represent the corresponding components at the county level based on previous studies and data availability (table 1).

2.3. Reforestation programs: the GFGP
In the study area, the GFGP is designed to return marginal farmlands back to forest lands by providing farmers with subsidies; this is also called the Returning Farmland to Forest Program (Zhang et al 2017, Qiu et al 2022). This program aims to combat land degradation, protect the downstream ecosystem and alleviate local poverty (Delang and Yuan 2015). Following the study by Tong et al (2018), the county-level inventory data were used in this study, which provided information about the plantation area for each year between 2000 and 2015. Then the accumulated plantation area was calculated for the 16 years within a given county, which was further divided by the total land area of that county to eliminate the influence of county size and to represent the GFGP effort in that county.
2.4. Ecological outcomes: vegetation greenness and production

Ecological outcomes are the primary goals of reforestation programs, which should be focused on vegetation growth and ecosystem function. In detail, vegetation greenness characterizes the vegetation growth state, whereas terrestrial GPP refers to the rate of carbon fixation or gross assimilation per unit ground surface area, revealing the vital ecosystem function of carbon absorption by plants via photosynthesis (Turner et al. 2006, Li and Xiao 2019). The selected indicators in this study were the EVI, which can effectively characterize vegetation states when there are dense vegetation conditions (Huete et al. 1997), and GPP, derived through solar-induced chlorophyll fluorescence (SIF), which can monitor ecosystem photosynthesis directly (Joiner et al. 2011).

The two metrics were obtained from two kinds of datasets. The EVI time-series dataset originated from Moderate Resolution Imaging Spectroradiometer (MODIS) vegetation index products (MOD13 EVI) (https://modis.gsfc.nasa.gov/data/dataprod/mod13.php) and the SIF-GPP can be obtained from the GOSIF datasets (https://globalecology.unh.edu/data/GOSIF.html), with the initial SIF data being derived from the Orbiting Carbon Observatory-2 satellite (Li and Xiao 2019). The 16 d, 250 m MODIS-EVI dataset and the maximum-value method were applied to obtain the monthly value. Non-vegetated pixels with EVI < 0.2 were omitted. The EVI dataset was used to calculate the average growing season (April–November in the study area) value, which was regarded as a proxy for the annual vegetation growth state (Tong et al. 2018). The annual GOSIF-GPP products with spatial resolution of 0.05° were used directly without further data manipulation.

Although environmental factors can affect vegetation growth, previous studies have shown that the reforestation program is the primary factor explaining vegetation dynamics in the study area (Tong et al. 2018). Therefore, the temporal changes of the two

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### Table 1. Variables used in this study.

| Component                  | Variable | Description                                                                                           | Calculation in this study                                                                 |
|----------------------------|----------|--------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------|
| Reforestation programs     | GFGP effort | To quantify the area of GFGP implementation                                                             | The ratio of the accumulated area of the GFGP and the total area of the given county during the study period, obtained from inventory data |
| Societal changes           | Rural outmigration | To quantify the released population pressure and livelihood transition from on-farm to off-farm. It involves multiple causes, such as urbanization, industrialization or competition of labor, and may lead to abandoned land and less human disturbance to forests | Rural population density change within a given county between 2000 and 2015, calculated from the grid population data and urban boundaries |
| Land system changes        | Farmland decrease | To quantify the changes of farmland that can be caused by GFGP implementation, spontaneous marginal farmland abandonment and expansion of urban areas. Only some parts of the former farmland can be successfully converted to forest lands due to various limitations | Change in proportion of farmland within a given county between 2000 and 2015, calculated using the land-use map |
| Ecosystem outcomes         | Forest land increase | To quantify the area of forest expansion. The initial forest transition is characterized by areal information about forest land that shows decreases or increases | Change in proportion of forest land within a given county between 2000 and 2015, obtained from the land-use map |
|                            | Vegetation greenness | To quantify the change in vegetation coverage during implementation of the GFGP, reflecting the growth state of green vegetation and the density of the vegetation canopy | The ratio between areas with significant positive trends in vegetation greenness during the study period and the total area of the given county. The vegetation greenness was measured by EVI derived from satellites at a resolution of 250 m |
|                            | GPP       | To quantify critical ecosystem functioning dynamics during GFGP implementation, which is highly related to biomass carbon sequestration | The ratio between areas with significant positive trends in vegetation production during the study period and the total area of the given county. GPP was set as the basic metric |
indices (i.e. EVI and GPP) were used to quantify the two types of ecological outcomes. In order to quantify the long-term ecological effects, areas with significantly increasing trends of EVI and GPP during the study period were counted within each county to represent the increased degree of vegetation greenness and GPP, respectively. For the trend calculation, the annual EVI (2000–2015) and GPP (2001–2015) trends were evaluated by the Mann–Kendall test, a non-parametric test that detected monotonic trends in time-series data. The function \( \text{zyp.trend.vector} \) was used with the Yue–Pilon pre-whitening method provided by the \( R \) package \( \text{zyp} \) to conduct the trend test (Bronaugh and Werner 2013). Trends with a \( p \)-value of \( \leq 0.05 \) were considered to be statistically significant in this study.

2.5. Societal changes: rural outmigration

The GFGP encouraged rural residents to leave farmland and seek alternative job opportunities (Cai et al 2014, Zhang et al 2017). Rural outmigration can quantify such societal changes. This indicator can also provide information about some other societal changes, such as rural livelihood transition induced by urbanization and industrialization, ecological outmigration and educational improvement (Yang et al 2018, Wu et al 2019, Rudel et al 2020). Thus, the changes in rural population density were used to indicate rural outmigration at the county level. Firstly, the grid population with 1 km resolution was obtained from the Resource and Environment Science and Data Center (www.resdc.cn/) (Xu 2017), which was more accurate than the Worldpop dataset (www.worldpop.org/) after validating the two datasets with statistical data. Secondly, urban population data were extracted using the urban boundaries from the Global Artificial Impervious Area dataset (http://data.ess.tsinghua.edu.cn/gub.html) and the rural population in the years 2000 and 2015 for each county was calculated (Li et al 2020). Finally, rural outmigration was measured through subtracting the 2015 rural population density from the 2000 rural population density.

2.6. Land system changes: total change in area of farmland and forest land

Forest land area is a core indicator in forest transition theory. However, when considering the GFGP, both increases in forest land and decreases in farmland need to be considered because the reduced farmland could be converted to forest lands as well as other land-use types. The changes in forest land and farmland represent two successive processes of the GFGP (i.e. reducing farmland and establishing new forest land). Land-use data produced by the Chinese Academy of Sciences at 30 m spatial resolution were used for the years 2000 and 2015. In this land-use classification system, forest land refers to the pixels identified as having natural, semi-natural and artificial vegetation, i.e. 0.5–30 m in height and where the vegetation cover is more than 20%. The proportional changes of farmland and forest land between 2000 and 2015 within each county were then calculated.

2.7. Structural Equation Model

Based on the hypothesized mechanisms (shown in figure 2(b)) and the above indicators (shown in table 1), SEM was used to quantify the multivariate causal network in which GFGP effort, rural outmigration, farmland decrease and forest land increase, and vegetation greenness/GPP were included. SEM, as a multivariate statistical analysis technique, is able to quantify the hypothesized relationships among variables and to test the plausibility of the assumed model using the observed data (Bollen and Noble 2011). Path analysis is one of the major applications of SEM without latent variables in the hypothesized model, and is suitable for testing whether the hypothesized causations shown in figure 2(b) are acceptable.

Three steps of the analysis were developed as follows. Firstly, Spearman correlation analysis was applied to quantify the interactions between pairs of components and to test whether these variables showed significant correlations. Meanwhile, to avoid multicollinearity influencing model performance, the variance inflation factor (VIF) of the variables was also calculated; this should be lower than 3.0. Secondly, path analysis of SEM was used to test whether the hypothesized relationships shown in figure 2(b) among the candidate variables were acceptable (Yang et al 2018). A set of validation indices that were used to test the fitness of the model should be met, and thus the hypothesized pathways can be confirmed. The following indices and criteria were included: \( p \)-values of \( \chi^2 \) and the goodness of fit test \( p > 0.05 \); the comparative fit index >0.9; and lower 90% confidence intervals for the root mean square error of approximation <0.05. The path coefficients could be identified in this step. Lastly, path coefficients were used to calculate the effect of each path through which the GFGP affected ecological outcomes. The net effects transmitted through observed components, the effects transmitted through the direct pathways and the total effects could be quantified by multiplying the path coefficients. The significance of the effects of each pathway also needed to be tested. All above calculations were conducted using the ‘sem’ and ‘lavaan’ packages in \( R \) software.

3. Results

3.1. Spatial distributions of ecological outcomes

A total of 47.15% of the study area showed a significant increase in EVI between 2000 and 2015, and only 1.30% of the region showed significant decreases in EVI, meaning that nearly half of the study area
underwent significant vegetation growth or regeneration (figure 3(a)). In contrast, a total of 82.24% of the study area showed a significant increase in GPP (figure 3(b)). The spatial distributions of the change trends for EVI and GPP were quite similar. Both increases were clearest in the west and north of the province, which had higher elevation and more proportion of karst landforms.

3.2. Component interactions and pathways

The correlation coefficients among pairs of components showed significant positive correlations between GFGP effort and vegetation greenness/GPP ($r = 0.547$ and $0.457$, respectively; $p < 0.001$) (figure 4). GFGP effort also showed a significant positive correlation with farmland decrease ($r = 0.216$, $p = 0.051$), but no significant correlation with rural outmigration. In contrast, there was a significantly negative relationship between GFGP effort and forest land increase ($r = -0.195$, $p = 0.079$).

The SEM results further showed the linkages between different components (figure 5): the GFGP influenced vegetation greenness and GPP in both direct and indirect ways (figure 5 and table 2). The total
Figure 5. Impacts of socio-economic transitions on vegetation greenness and GPP. Blue and red arrows indicate positive and negative impacts, respectively; $R^2$ indicates the proportion of variance explained; solid arrows represent significant pathways ($p \leq 0.1$); dashed arrows represent non-significant pathways ($p > 0.1$).

Table 2. The effects of pathways through which the GFGP influenced vegetation greenness and GPP.

| Pathways                                                                 | Effects | Greenness | GPP    |
|--------------------------------------------------------------------------|---------|-----------|--------|
| Direct pathway:                                                         |         |           |        |
| GFGP effort $\rightarrow$ vegetation                                    |         | 0.565$^a$ | 0.451$^a$ |
| Indirect pathways:                                                       |         |           |        |
| GFGP effort $\rightarrow$ farmland decrease $\rightarrow$ vegetation    |         | $-0.174^b$ | $-0.091^c$ |
| GFGP effort $\rightarrow$ farmland decrease $\rightarrow$ forest land increase $\rightarrow$ vegetation |         | 0.003     | 0.001  |
| GFGP effort $\rightarrow$ forest land increase $\rightarrow$ vegetation |         | 0.037     | 0.011  |
| GFGP effort $\rightarrow$ rural outmigration $\rightarrow$ farmland decrease $\rightarrow$ vegetation |         | $-0.038^c$ | $-0.020$ |
| GFGP effort $\rightarrow$ rural outmigration $\rightarrow$ farmland decrease $\rightarrow$ forest land increase $\rightarrow$ vegetation |         | 0.001     | 0.000  |
| GFGP effort $\rightarrow$ rural outmigration $\rightarrow$ vegetation |         | $-0.006$ | $-0.065$ |
| Total                                                                    |         | 0.388$^a$ | 0.263$^b$ |

$^a p \leq 0.01$.  
$^b p \leq 0.05$.  
$^c p \leq 0.1$.  

Effect of the GFGP on vegetation greenness and GPP was 0.388 and 0.263, respectively, suggesting that a 1% increase in the area of GFGP implementation within a county would lead to a 0.388% increase in the area with a significantly ($p < 0.001$) greening trend and a 0.263% increase in the area with a significantly ($p < 0.05$) GPP increasing trend. For the direct pathways, the partial effects ($r_\partial$) of the GFGP on vegetation greenness and production were significantly positive ($r_\partial = 0.565$, $p < 0.001$ and $r_\partial = 0.451$, $p < 0.001$, respectively). For indirect pathways, two showed statistical significance ($p < 0.1$) to explain the lower increasing area with increased greenness, and one significantly ($p < 0.1$) explained the lower increasing area with increased GPP. The GFGP negatively affected the increase in area with significantly increasing greenness and GPP through the pathways boosting decreased farmland, which led to a smaller area showing a significant greening trend ($p = 0.069$). Therefore, this indirectly negative pathway of the GFGP on the greening landscape (i.e. more areas showing a significantly increasing trend in EVI) was mainly realized by reducing farmland and encouraging rural outmigration, while the indirectly negative pathway of the GFGP on a more productive landscape was only enabled by reducing farmland.

4. Discussion

4.1. Distinguishing the ecological outcomes of pathways

Distinguishing the different influencing pathways during forestation programs can improve our understanding of the failures or successes of each part of the human intervention and hence improve the final ecological outcomes accordingly (Liu et al 2007, Ferraro and Hanauer 2014, Yang et al 2018). Several pathways were obtained through the SEM results in this study (figure 6). The first was the pathway in which GFGP directly enhanced vegetation greenness and productivity, showing significantly positive effects ($r_\partial = 0.565$...
The second type of indirect pathway considered societal change indicated by rural outmigration, namely the social transition pathway (figure 6). Among the pathways involving rural outmigration, the GFGP boosted outmigration and then reduction in farmland, and only imposed significantly negative effects ($-0.038, p < 0.1$) on increasing the greening area, with no significant effects on GPP (table 2). The results revealed that the program motivated rural outmigration and farmland reduction because incentivization policies encouraged farmers to abandon marginal farmland and to pursue alternative livelihoods (Cai et al. 2014, Wu et al. 2019). However, similar to the effects imposed by the land-use alteration pathway, such societal and land-use changes did not contribute to the achievement of ecological goals. This was mainly because the conversion from crop plants to trees or grasses had not yet been completed within the study period, resulting in a decreasing trend or non-significant dynamics in terms of greenness and production. Another reason may lie in the difficulty of reforestation in the study area with rough natural conditions (Wang et al. 2019, Zhao et al. 2021).

The GFGP only explained 8.8% of the variance in rural outmigration and 29.7% of the variance in farmland reduction (figure 5), indicating that the GFGP was not the major explanation for rural outmigration and farmland reduction. Forest transition theory suggests that the passive pathway for socio-economic development could facilitate farmers to leave villages (Lambin and Meyfroidt 2010, Zhang et al. 2017). This mechanism can be termed the passive restoration pathway or the ‘fourth pathway’ (figure 6), which is not impacted by environmental policies but is caused by socio-economic considerations. In China, the policy of reforming and opening up since the 1980s has released household liquidity constraints and led to a boom in economic...
development; and hence rural laborers were encouraged to migrate to urban areas to seek job opportunities (Chen et al 2012, Cai et al 2014). Such societal changes passively contributed to land-use conversion and ecological restoration. The fourth pathway mainly occurred in developing areas where extensive land abandonment and large-scale tree planting occurred simultaneously (Uchida et al 2009, Lambin and Meyfroidt 2010, Redo et al 2012). Uncovering this pathway is a matter of the sustainability of ecological outcomes because the impacts generated by this pathway are induced by farmers’ self-interests. It will be a great challenge if they come back to villages and destroy the forest plantation if they cannot achieve competitive salaries in the cities.

Among the above pathways, the direct conservation pathway produced the most positive effects in both SEMs, indicating that government-led reforestation programs effectively lead to a greening and more productive landscape. During this process, although the GFGP boosted the quitting of farmland by rural residents, it was not easy to convert this land into forest lands and thus to achieve a more greening or productive landscape. In the context of the growing forest that has been planted on former agricultural landscapes, this study offers some implications for future large-scale investment in extensive reforestation (Heilmayr et al 2020, Rudel et al 2020, Meier et al 2021). Although more investment in reforestation does not necessarily lead to increased forest expansion, the contributions made by shifting the livelihoods of local farmers and conserving ecosystem functioning are potentially useful when diverse social–ecological goals are being considered.

4.2. Extending forest transition theory
Previous forest transition studies have provided insights into how societal changes impacted the land system. However, they only explained the forest area and did not investigate the effects of changes in density and function (Kauppi et al 2020). Even in a region with a net increase in forest land within a certain period, there would be young trees with lower production. In addition, the trees may experience extreme climate events with distinct degradation. Just quantifying forest area runs the risk of inaccurately estimating the effects of widespread forest expansion on climate change mitigation or biodiversity conservation. The results show that compared with the area of forest land expansion in the study area, the areas with significantly increasing EVI and GPP were both far greater, suggesting that only quantifying land-use area cannot accurately estimate the contribution of reforestation efforts. In this study, it was found that there were pair relationships between EVI/GPP and GFGP effort ($r = 0.547$ for EVI and $r = 0.457$ for GPP, both $p < 0.001$). Furthermore, the relationship between forest increase and GFGP effort was negative ($r = -0.195$, $p < 0.1$, figure 4), which confirmed that more attributes of biomass dynamics should be considered when trying to understand the effects of reforestation programs. Forest transition theory should also be extended to link societal changes with biophysical components more deeply (Fang et al 2014, Jadin et al 2016, Kauppi et al 2020). Such extended use of the theory could help us better understand how societal changes influenced forests in terms of quality and quantity, leading to appropriate human interventions not only in the way of directly planting trees but also determining social approaches.

4.3. Limitations and future research directions
The key aim of this study was to identify the pathways by which reforestation programs affect ecological outcomes. However, only some of the influencing factors were considered, with reforestation activities as the initial driver. Social factors, such as the structure of rural residents, may also influence forest change, and can be considered in future studies. Furthermore, the spatial resolution of the GOSIF dataset is 0.05°, which is a little coarse when attempting to measure the change trend of GPP. The dataset might have overestimated the areas with significant GPP change trend. It is also worth noting that GOSIF-GPP, as a relatively independent earth observation dataset, can reflect the actual photosynthetic ability of vegetation. In addition, time lag should be given a greater focus in future studies, as several years may be needed to capture with remote sensing technologies the changes in forest canopy cover after actual reforestation, and hence the contribution of the GFGP on forest areal expansion might be underestimated (Coleman et al 2021).

5. Conclusions
Large-scale forestation programs have been developed around the globe to restore degraded ecosystems. However, current forestation programs do not merely involve tree-planting activities, but also include social components and their impacts on the ecosystem. In this study, two remote sensing based indicators were used to explore the direct and indirect effects of reforestation programs on different components. It was found that implementation of the GFGP encouraged more rural out-migration and reduced farmland. Although it did not lead to highly increased expansion of forest area, it did improve vegetation growth and production. This study links human-induced forestation practice with ecosystem structure and function feedbacks through complex social–ecological processes, and provides new insights for the better design of forestation programs.
Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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