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Original Research

Spatiotemporal Variations of NDVI and Their Responses to Climate Change and Human Activities in Guizhou, China (2000-2020)

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Abstract

The low spatial resolution of vegetation index data has limited comprehensive studies on the impacts of human activities on vegetation cover. In this context, the spatiotemporal variations of the Landsat-derived Normalized Difference Vegetation Index (NDVI) and its responses to air temperature, precipitation, and land cover changes in Guizhou Province, China, were analyzed from 2000 to 2020 at a spatial resolution of 30 m. The results showed: (1) NDVI exhibited a significant linear increasing trend, with a rate of change of 0.0033 per year ($P<0.05$). (2) NDVI values were positively correlated with mean annual air temperatures and annual precipitation across 79.12% and 80.44% of the total provincial area, respectively. (3) The decreasing rate of NDVI values in constructed areas was more than twice the increasing rate of NDVI values in areas where mutual conversion among cultivated land, forest, and grassland was observed. Moreover, the decreasing rate of the difference between the mean annual NDVI of areas where cultivated land, forest, and grassland were converted to constructed area, and the initial mean annual NDVI was over ten times higher than the decreasing rate in areas where forest and grassland were converted to cultivated land. This research suggested that controlling the conversion of forests and grasslands to cultivated land and strengthening the regulation of human activities (especially urban expansion) are of great importance for improving the provincial vegetation coverage level and the stability of the vegetation ecosystem.

Keywords: climate change, vegetation type, linear regression, correlation coefficient, Guizhou Province of China

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Introduction

Vegetation plays a crucial role in global terrestrial surface ecosystems through various functions, such as climate regulation, carbon sequestration, oxygen release, food provision, and preservation of ecological balance [1, 2]. However, vegetation ecosystems in ecologically fragile areas (e.g., high-latitude and high-altitude regions) are relatively sensitive to ongoing climate change [3, 4]. Karst landforms are well developed in the Yunnan-Guizhou Plateau in Southwest China, which is characterized by severe rocky desertification, resulting in a fragile ecology [5-7]. Guizhou Province has successively implemented the Grain for Green Project (GGP) and the Comprehensive Control Project of Rocky Desertification (CCPRD), and has become one of the first national ecological civilization pilot zones in China [8, 9]. Research on changes in vegetation ecosystems in ecologically fragile areas under current climate change, GGP and CCPRD implementation, and urban expansion is of great theoretical and practical significance for understanding regional vegetation ecosystem trends and for developing policies to support vegetation restoration and development.

The Normalized Difference Vegetation Index (NDVI) has been extensively applied in studies on dynamic changes in terrestrial surface vegetation due to its simple calculation, easy accessibility, and ability to accurately capture vegetation changes [10-12]. The major current NDVI datasets include GIMMS-NDVI, MODIS-NDVI, SPOT-NDVI, and Landsat-NDVI. Among these, GIMMS-NDVI is a 15-day dataset with an 8 km spatial resolution, covering the 1982-2022 period. This dataset has been widely used in studies on global and regional vegetation changes [13-18]. MODIS-NDVI, on the other hand, has daily, 8-day, 16-day, monthly, and annual data dating back to 2000, with spatial resolutions of 1 km, 500 m, and 250 m, and has been extensively employed in related regional-scale research [19-22]. SPOT-NDVI has been available as 10-day-interval data, with a 1 km spatial resolution since 1998, and its applications have also focused on regional-scale vegetation changes [23-25]. Landsat-NDVI is calculated based on the spectral bands of Landsat images, dating back to the 1980s. However, the application of this dataset in large-scale, long-term related studies (e.g., provincial and regional scales) remains challenging due to the impacts of various factors, such as the relatively high spatial resolution (30 m) of the Landsat images, the satellite revisit periods (16 days and 18 days), and cloud interference. This has limited its application to small-scale research [26-28]. However, the 30-m Landsat-based long-time-series NDVI produced by Yang et al. (2019) [29] provides higher-resolution data for conducting mesoscale vegetation change research, reflecting the impacts of human activities on vegetation.

Although GIMMS-NDVI, MODIS-NDVI, and SPOT-NDVI have the advantages of multiple resolutions and good time-series performance, their relatively low spatial resolution allows them to reflect the impact of climate change on NDVI but is insufficient for capturing the effects of human activities, especially urban expansion and the implementation of GGP and CCPRD. Moreover, since the study area of this paper, Guizhou Province, is dominated by mountainous terrain, Landsat NDVI data with a 30-m spatial resolution are more effective for reflecting the impacts of GGP and CCPRD.

Guizhou Province in China is an ecologically fragile region where extensive research on the relationship between vegetation changes, climate change, and human activities has been conducted. Luo et al. (2021) [30] concluded that human activities and nature reserves can coexist in Guizhou Province from 1988 to 2019. Huang et al. (2022) [31] argued that the implementation of CCPRD in Guizhou Province has effectively improved the connectivity of vegetation landscapes and vegetation coverage. Xue et al. (2023) [32] suggested a trend of improvement in vegetation coverage in Guizhou Province from 2000 to 2021. Wei et al. (2021) [33] also argued that the impact of air temperatures on vegetation in Guizhou Province was stronger than that of precipitation over the 1982-2015 period. Furthermore, the contribution of human activities, including ecological restoration projects, to vegetation changes was estimated at 76%, while that of climatic factors was only 24%. Guo et al. (2023) [34] indicated that the conversion of cultivated land to forests in Guizhou Province from 1980 to 2018 was effective in promoting the increase in forest coverage. Those studies have quantitatively distinguished the respective contributions of climate change and human activities to vegetation dynamics [30-34]. However, human activities exert dual effects on vegetation change, with positive and negative impacts occurring simultaneously. For example, the GGP and CCPRD have positive effects and promote vegetation improvement, whereas urban expansion has negative effects and leads to vegetation degradation [35]. Limited by the spatial resolution of NDVI data (for instance, the effects of the GGP on vegetation improvement were severely underestimated in the Loess Plateau using 250-m-resolution MODIS NDVI), these studies have failed to distinguish the directional characteristics of human activities on vegetation change and cannot accurately identify the separate effects of the GGP, CCPRD, and urban expansion on vegetation dynamics.

In this context, the present paper aims to analyze the spatiotemporal variations of NDVI and their responses to climate change (air temperature and precipitation) and land cover change – reflecting the effects of the GGP, CCPRD, and urban expansion – in Guizhou Province during the period 2000-2020. This analysis is based on 30-m-resolution Landsat NDVI, air temperature, precipitation, and land cover data. The results provide scientific support for understanding the effects of the GGP, CCPRD, and urban expansion on vegetation change and for improving vegetation restoration and protection policies in Guizhou Province, China.

Materials and Methods

Study Area

Guizhou Province is located in Southwest China, with its geographical coordinates ranging from 103°36′17.60″E to 109°36′14.39″E and from 24°37′12.40″N to 29°12′2.70″N. It is bordered by Hunan Province, the Guangxi Zhuang Autonomous Region, Yunnan Province, and Sichuan Province and Chongqing Municipality to the east, south, west, and north, respectively, covering a total land area of 176,100 km² (Fig. 1). Geomorphologically, the study area belongs to the Yunnan-Guizhou Plateau, where the terrain in the western part is higher than that in the eastern part, sloping northward, eastward, and southward from the central part, with altitudes ranging from 148 m to 2,885 m. It is characterized by a subtropical humid monsoon climate. From 1990 to 2020, the mean annual air temperature and annual precipitation were 16.31ºC and 1,194.13 mm, respectively.

The vegetation types in Guizhou Province are shaped by latitude and topography, including tropical and subtropical vegetation (e.g., monsoon and evergreen broad-leaved forests), as well as temperate and cold-temperate vegetation (e.g., deciduous broad-leaved and subalpine coniferous forests). There are numerous rivers in the province, belonging to two major river systems, namely the Yangtze River and the Pearl River. The province serves as an important ecological barrier and water conservation area for the tributaries of the Yangtze River and the upper reaches of the Pearl River. In 2020, the main land cover types in Guizhou Province were forest, cultivated land, and grassland, accounting for 44.90%, 33.73%, and 17.96% of the total provincial area, respectively. In contrast, constructed area accounted for only 1.66% of the total provincial area.

Guizhou Province is one of the regions with the most typical and extensive karst landform development in the world, where exposed karst landforms account for 61.92% of the province's total area [36]. It is also the province in China with the largest area affected by rocky desertification and the most severe associated hazards [37, 38]. Influenced by the Southwest Monsoon in East Asia, heavy rainfall in Guizhou Province is highly concentrated within a short period, resulting in severe soil erosion and a fragile ecology. In recent years, the implementation of major ecological restoration projects and policies, including the GGP, the CCPRD, and the establishment of national ecological civilization pilot zones, has effectively promoted the restoration and development of vegetation ecosystems in Guizhou Province. As a result, vegetation coverage has increased remarkably, and the ecological environment has shown steady improvement [8, 9]. Consequently, Guizhou Province has become a typical study area for investigating the impacts of climate change and human activities on vegetation dynamics. The findings from this region provide valuable references for rocky desertification control and the coordinated development of human-land systems in karst regions in China and worldwide.

Materials

In this study, long-term Landsat-derived annual NDVI data from 2000 to 2020, with a 30-m spatial resolution, were used. Specifically, the annual NDVI values were determined using the pixel-by-pixel maximum-value composite (MVC) method [29]. These

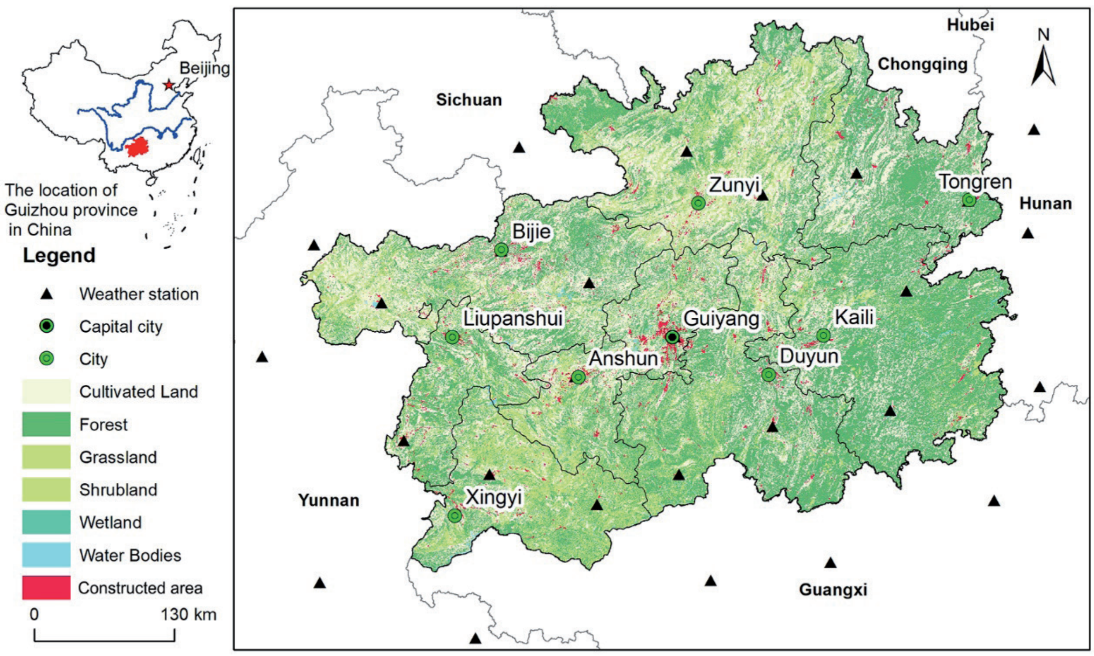

Fig. 1. Geographical location of the study area and the spatial distribution of meteorological stations.

data were downloaded from the National Ecosystem Science Data Center, National Science & Technology Infrastructure of China (http://www.nesdc.org.cn). Mean daily air temperature and daily precipitation data at 29 meteorological stations in Guizhou Province and its surrounding areas, covering the period from 2000 to 2020, were also collected in this study from the National Meteorological Science Data Center (data.cma.cn) (Fig. 1). Digital Elevation Model (SRTM-DEM) data, with a 90 m resolution, were downloaded from the Geospatial Data Cloud (www.gscloud.cn). The 30-m global land cover type data, including ten land cover types (cultivated land, forest, grassland, shrubland, wetland, water bodies, tundra, constructed area, bare land, permanent snow/ice), were acquired in this study. The vector boundary of Guizhou Province was downloaded from the Resource and Environment Science Data Platform (www.resdc.cn). Among the above-mentioned data, the average daily air temperature and daily precipitation data were first converted into annual data by calculating the average value and summing up the total values, respectively. Subsequently, the Inverse Distance Weighting (IDW) interpolation method was used to generate the mean annual air temperature and annual precipitation data of Guizhou Province from 2000 to 2020, at a 30-m spatial resolution. The NDVI and global land cover type data were clipped according to the vector boundary of Guizhou Province.

Methods

Linear Regression Model

Linear regression was mainly used in this study to analyze the temporal variation trends of NDVI, according to the following equation [39]:

$$y = ax + b \tag{1}$$

$$a = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sum_{i=1}^{n}(x_i - \bar{x})^2} = \frac{\sum_{i=1}^{n} x_i y_i - \frac{1}{n}\sum_{i=1}^{n} x_i \sum_{i=1}^{n} y_i}{\sum_{i=1}^{n} x_i^2 - \frac{1}{n}(\sum_{i=1}^{n} x_i)^2} \tag{2}$$

where y denotes the dependent variable, representing the NDVI data for Guizhou Province from 2000 to 2020; x is the independent variable, representing the time range of the study period (2000-2020); a is the coefficient or linear changing rate. Specifically, positive or negative values indicate the direction of the change. b is a constant term; $\bar{x}$ and $\bar{y}$ are the average values of x and y, respectively.

The statistical significance of the linear regression model was evaluated using the F-test, according to the following equations [39]:

$$F = \frac{U}{Q(n-2)} \tag{3}$$

$$U = \sum_{i=1}^{n}(y_i^{'} - \bar{y})^2 \tag{4}$$

$$Q = \sum_{i=1}^{n}(y_i - y_i^{'})^2 \tag{5}$$

where y' denotes the fitted value of y, calculated using Eq. (1); n denotes the sample size. The threshold value (4.38) was obtained from the corresponding F-distribution table (when $\alpha = 0.05$ and $n = 21$).

Correlation Analysis

The correlation coefficient (r) is used to analyze the relationship between two variables. In this study, the correlation coefficient was mainly used to analyze the relationships between NDVI and the mean annual air temperatures and annual precipitation in Guizhou Province from 2000 to 2020. Its calculation formula was as follows [39]:

$$r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}} \tag{6}$$

where x denotes the NDVI values of Guizhou Province from 2000 to 2020; y is the mean annual air temperature or annual precipitation from 2000 to 2020; $\bar{x}$ and $\bar{y}$ are the average values of x and y, respectively. The statistical significance of the correlation was evaluated according to the above-mentioned threshold value of 0.4329 (when $\alpha = 0.05$ and $n = 21$). Specifically, $|r|>0.4329$ and $|r|<0.4329$ indicate statistically significant and non-significant correlations between the variables, respectively.

Results and Discussion

Temporal and Spatial Variations in the NDVI-Based Vegetation Coverage

Temporal Variations in the NDVI-Based Vegetation Coverage

The mean annual NDVI values in Guizhou Province increased from 0.7359 to 0.8026 over the 2000-2020 period, showing an overall statistically significant increasing trend, with a changing rate of 0.0033 per year ($P<0.05$), and the result was consistent with the performance in other regions of China [40-42]. The study period can be classified into two distinct phases based on the variations in the NDVI values. The first phase (2000-2011) was divided into two increase-decrease cycles (2000-2005 and 2005-2011), corresponding to a mean annual value of 0.7530. The second phase, on the other hand, was observed in the 2011-2020 period, during which the mean annual value of the NDVI was 0.7875, presenting a fluctuating upward trend (Fig. 2a)). The obtained results revealed negative and positive anomaly values of the NDVI in Guizhou from 2000 to 2012 and from 2013 to 2020, respectively (Fig. 2b)), indicating an improvement in vegetation coverage in the 2013-2020 period. The above results may reflect the role of GGP and CCPRD in improving vegetation in Guizhou Province.

Spatial Variations of the NDVI-Based Vegetation Coverage

Spatially, the distribution of the changing NDVI rates in Guizhou Province ranged from -0.0525 to 0.0500 per year over the 2000-2020 period. Generally, it showed a spatial distribution characteristic in which the changing rates were low in the southeast, northwest, and surrounding areas of cities, while the highest values were found in the northeast, southwest, and central-southern regions (Fig. 3a)). In terms of variation trends, NDVI values in Guizhou Province were dominated by an increasing trend from 2000 to 2020 in 92.23% of the total provincial area. In particular, regions with a significantly increasing trend accounted for 75.16% of the total area, and were distributed in all areas except the southeast, central part, and surrounding areas of cities. In contrast, regions with a significantly decreasing trend accounted for only 2.70%, and were concentrated in the surrounding areas of cities, such as Guiyang (Fig. 3b)). The spatial variation and distribution characteristics of the NDVI values in Guizhou Province reflected the relatively strong impacts of human activities, especially urban expansion, on vegetation. Therefore, vegetation farther away from urban areas is less affected by urban expansion, with higher NDVI values and more significant vegetation improvement, reflecting the clear

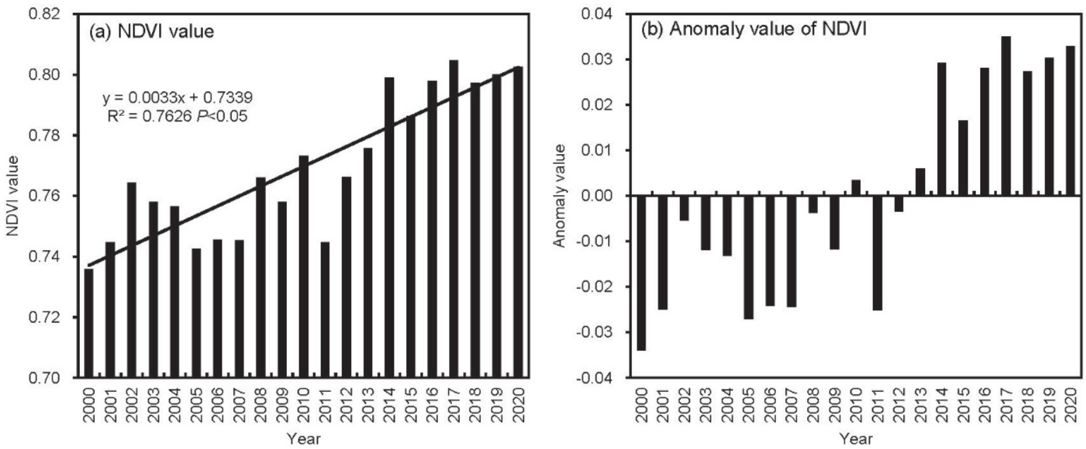

Fig. 2. Temporal variations in the a) annual and b) anomaly value of NDVI in Guizhou Province from 2000 to 2020.
Note: The anomaly values of NDVI are defined as the difference between the NDVI value in each year and the average NDVI value of Guizhou Province during the 2000-2020 period.

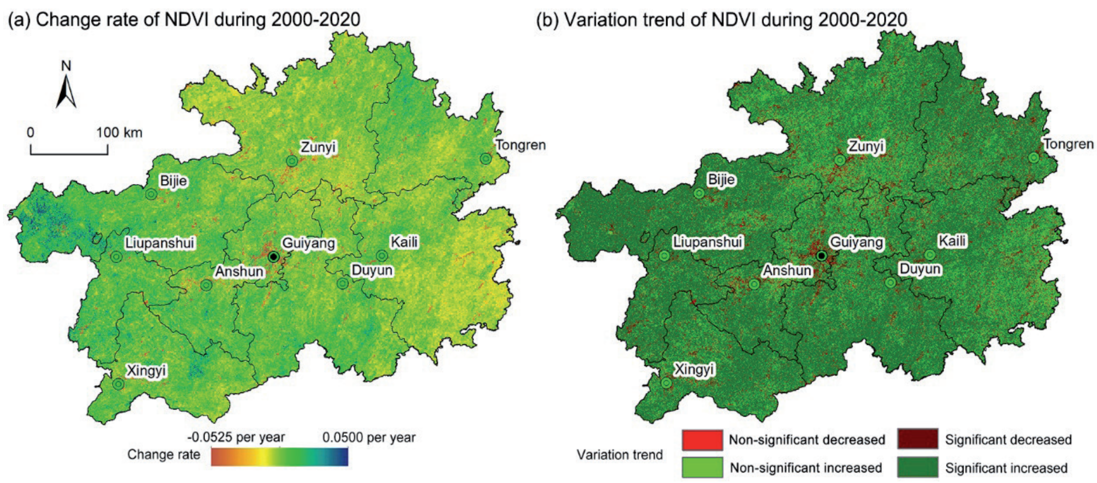

Fig. 3. Spatial distributions of the a) rates of change and b) variation trends of the NDVI-based vegetation coverage in Guizhou Province from 2000 to 2020.

negative effect of urban expansion on vegetation. As the province with the largest concentration of ethnic minorities in China, Guizhou's scattered residential pattern has a relatively small negative impact on vegetation.

Relationships between the NDVI, Air Temperature, and Precipitation

The formation and changes in vegetation ecosystems are controlled by climate and its characteristics. Air temperature and precipitation are not only the two most critical factors affecting vegetation growth, but also the most important indicators of global climate change. The mean annual air temperature and precipitation at the 29 meteorological stations in Guizhou Province and its surrounding areas exhibited increasing trends over the 2000-2020 period from 15.79ºC to 16.42°C and from 1,268.22 mm to 1,425.67 mm, respectively. Specifically, the changing rates of the mean annual air temperature and precipitation were 0.21ºC per decade and 75.87 mm per decade, respectively, but without

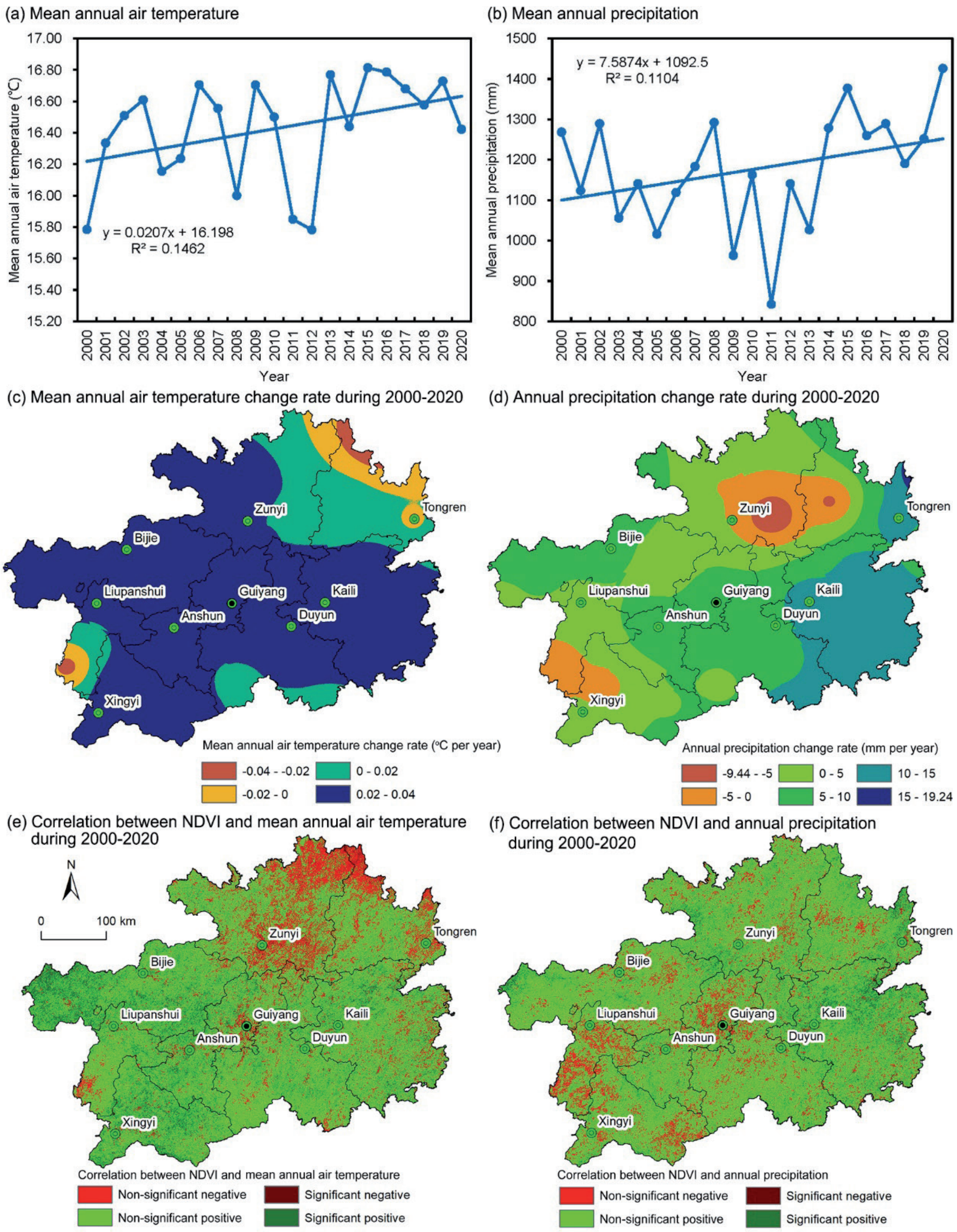

Fig. 4. Temporal variations in the a) mean annual air temperature and b) precipitation; spatial variations in the c) mean annual air temperature and d) precipitation; spatial distributions of the correlation coefficients between the NDVI and e) mean annual air temperature, as well as f) mean annual precipitation, in Guizhou Province from 2000 to 2020.

statistically significant increases at the $P<0.05$ level (Fig. 4a) and b)).

The spatial changing rates of the mean annual air temperature in Guizhou Province were generally positive in the 2000-2020 period, except for some small areas in the northern parts of the province, where the changing rates were negative (Fig. 4c)). Similarly, the changing rates of the annual precipitation were also dominated by positive values. The negative changing rates were found in relatively small areas in the northern and southwestern parts of the province (Fig. 4d)).

The correlations between the NDVI values and air temperature and precipitation values were further explored in this study over the 2000-2020 period. Overall, the NDVI values were mainly positively correlated with the mean annual air temperature in 79.12% of the total provincial area. Regions with significant positive correlations accounted for 19.15% of the total area, mainly distributed in the western, southwestern, and central parts of the province. In contrast, regions with significant negative correlations accounted for only 1.36%, concentrated in the northern part of the province (Fig. 4e)). Similarly, the NDVI values were mainly positively correlated with the annual precipitation in 80.44% of the provincial area. Regions with significant positive correlations accounted for 13.38%, particularly distributed in the western and eastern parts of the province. On the other hand, regions with significant negative correlations accounted for only 0.50% of the total study area (Fig. 4f)).

Overall, from 2000 to 2020, the climate in Guizhou Province was characterized by a warming and humidifying trend, with rising temperatures and increasing precipitation, while a small portion of the region exhibited a warming and drying trend. Vegetation increase was jointly promoted by natural and human factors, including climatic warming and humidification, as well as the implementation of GGP and CCPRD. The negative correlation between NDVI and air temperature/precipitation around urban areas reflects the dominant negative effect of urban expansion.

Responses of the NDVI-Based Vegetation Coverage to Land Cover Changes

Variations in the NDVI-Based Vegetation Coverage under Different Land Cover Types

Vegetation change is influenced by the combined effects of climate change and human activities, and some scholars argue that the impact of human activities

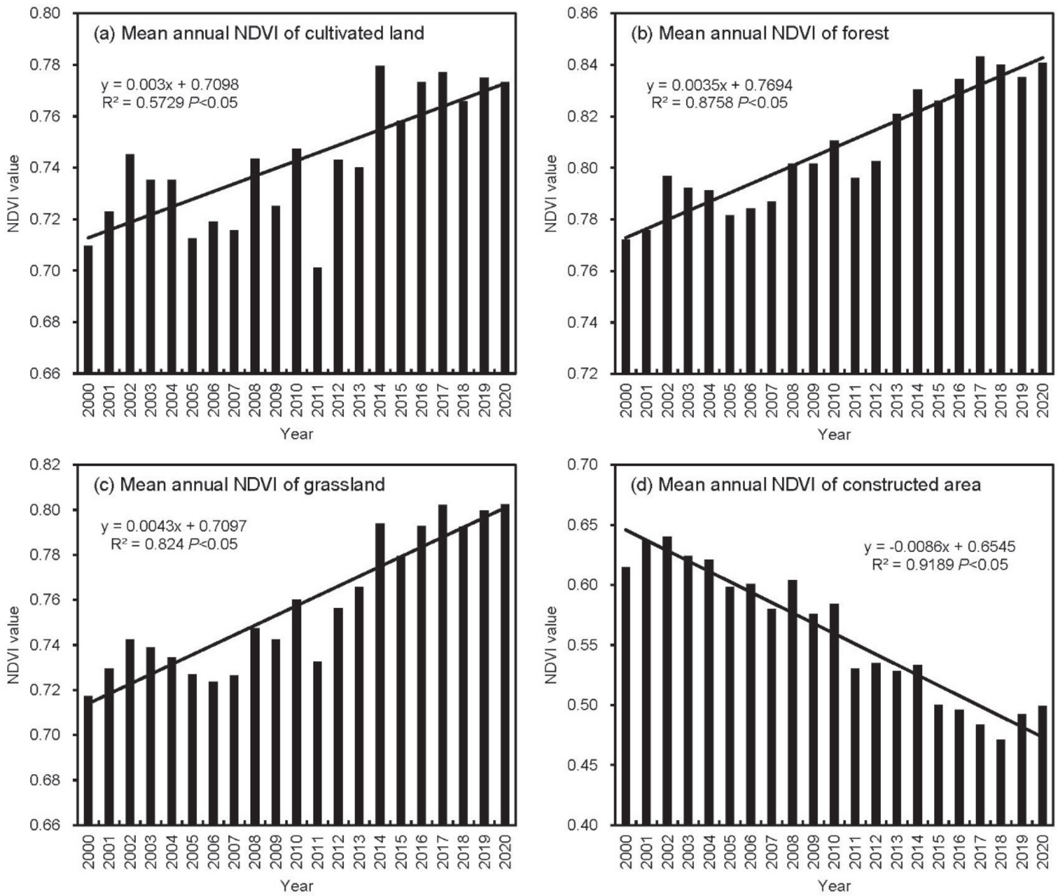

Fig. 5. Temporal variations in the NDVI values of a) cultivated land, b) forest, c) grassland, and d) constructed area in Guizhou Province from 2000 to 2020.

exceeds that of climate change [43-45]. In this study, land cover types were used to characterize human activities, with cultivated land and constructed area representing the most direct manifestations of human activities. Additionally, by incorporating forest and grassland, the land cover types with the largest areas in Guizhou Province in 2020, this study explored the relationship between vegetation change and human activities. The variations and differences in the mean annual NDVI values among cultivated land, forest, grassland, and constructed area from 2000 to 2020 were further explored in this study (Fig. 5 and Fig. 6).

The mean annual NDVI values of cultivated land, forest, grassland, and constructed area in Guizhou Province over the 2000-2020 period were 0.7428, 0.8079, 0.7575, and 0.5596, respectively, with a global mean annual NDVI value across the entire province of 0.7698. According to the obtained area proportions of the different land cover types in the province, it can be concluded that forests dominated the overall NDVI values temporally in Guizhou Province from 2000 to 2020.

The NDVI values of the cultivated land, forest, and grassland in Guizhou Province increased from 0.7097 to 0.7733, 0.7721 to 0.8409, and 0.7173 to 0.8024 over the 2000-2020 period, respectively, showing significant increasing trends. The changing rates were estimated at 0.0030 ($P<0.05$) (Fig. 5a)), 0.0035 ($P<0.05$) (Fig. 5b)), and 0.0043 per year ($P<0.05$) (Fig. 5c)) for cultivated land, forest, and grassland, respectively. Among them, grassland exhibited the highest increasing rate. This indicates that grassland played a role comparable to that of forest in the improvement of the NDVI-based vegetation coverage in Guizhou Province from 2000 to 2020. In contrast, the NDVI values of the constructed area decreased from 0.6150 in 2000 to 0.4992 in 2020, showing a significant decreasing trend, with a changing rate of -0.0086 per year ($P<0.05$) (Fig. 5d)). This finding highlights the negative role of the constructed area in vegetation improvement in Guizhou Province over the 2000-2020 period. This decreasing trend, however, might not substantially affect vegetation coverage in the study area due to the relatively small proportion of constructed area in the province.

The variations in the difference between the mean annual NDVI values among the different land cover types of Guizhou Province were further explored. Specifically, the difference in the mean annual NDVI values between cultivated land and the entire province area was consistently negative over the 2000-2020

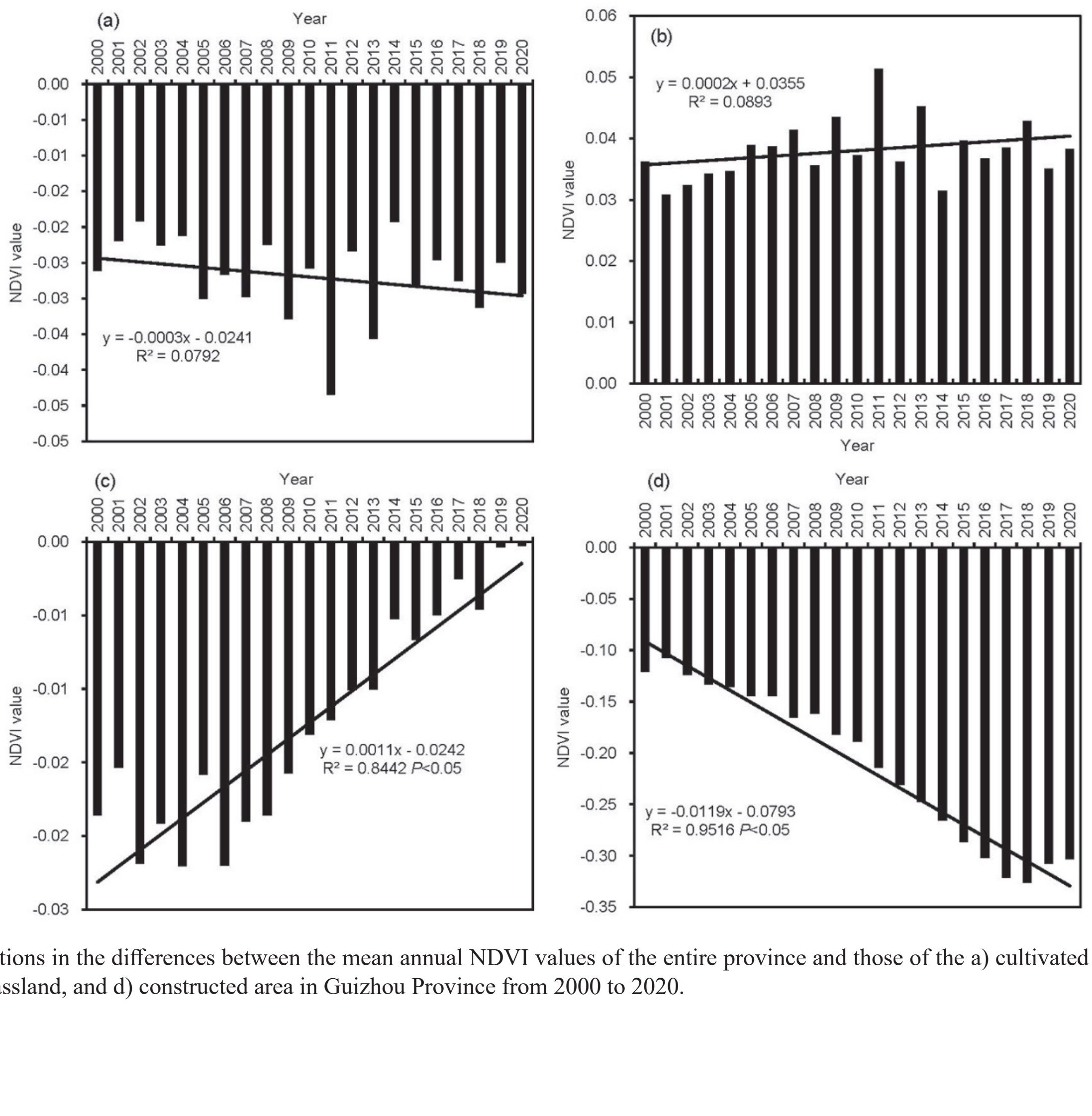

Fig. 6. Variations in the differences between the mean annual NDVI values of the entire province and those of the a) cultivated land, b) forest, c) grassland, and d) constructed area in Guizhou Province from 2000 to 2020.

period, showing increasing and decreasing trends in the 2000-2011 and 2011-2020 periods, respectively. The corresponding changing rate was -0.0003 per year without statistical significance at the $P<0.05$ level (Fig. 6a)).

The difference between the mean annual NDVI value of forest and that of the entire province was positive, showing an increasing trend, with a statistically non-significant linear changing rate of 0.0002 per year at the $P<0.05$ level (Fig. 6b)). On the other hand, the difference between the mean annual NDVI values of the grassland and the entire province was negative, and the declining trend weakened significantly, with a changing rate of 0.0011 per year ($P<0.05$). The difference in the mean annual NDVI between grassland and the entire province gradually decreased, reaching -0.0003 in 2020 (Fig. 6c)).

The difference between the mean annual NDVI values of the constructed area and the entire province was negative, indicating a significant linear decreasing trend, with a changing rate of -0.0119 per year ($P<0.05$). The difference between the mean annual NDVI values of the constructed area and the province exhibited a continuous widening over time (Fig. 6d)). In summary, the NDVI-based vegetation coverage in Guizhou Province was generally dominated by forest during the 2000-2020 period, with grassland contributing positively to improved vegetation cover at the provincial level, while constructed area had a negative effect.

In summary, forest dominates the overall NDVI level in Guizhou Province, and grassland has the fastest NDVI growth rate, playing a key role in promoting the rapid increase in provincial NDVI. Forest and grassland play an important role in improving vegetation conditions, while urban expansion has a significant effect in reducing NDVI levels.

Variations in the NDVI Values of Areas with Land Cover Changes

Areas where cultivated land, forest, and grassland were mutually converted or transformed to constructed

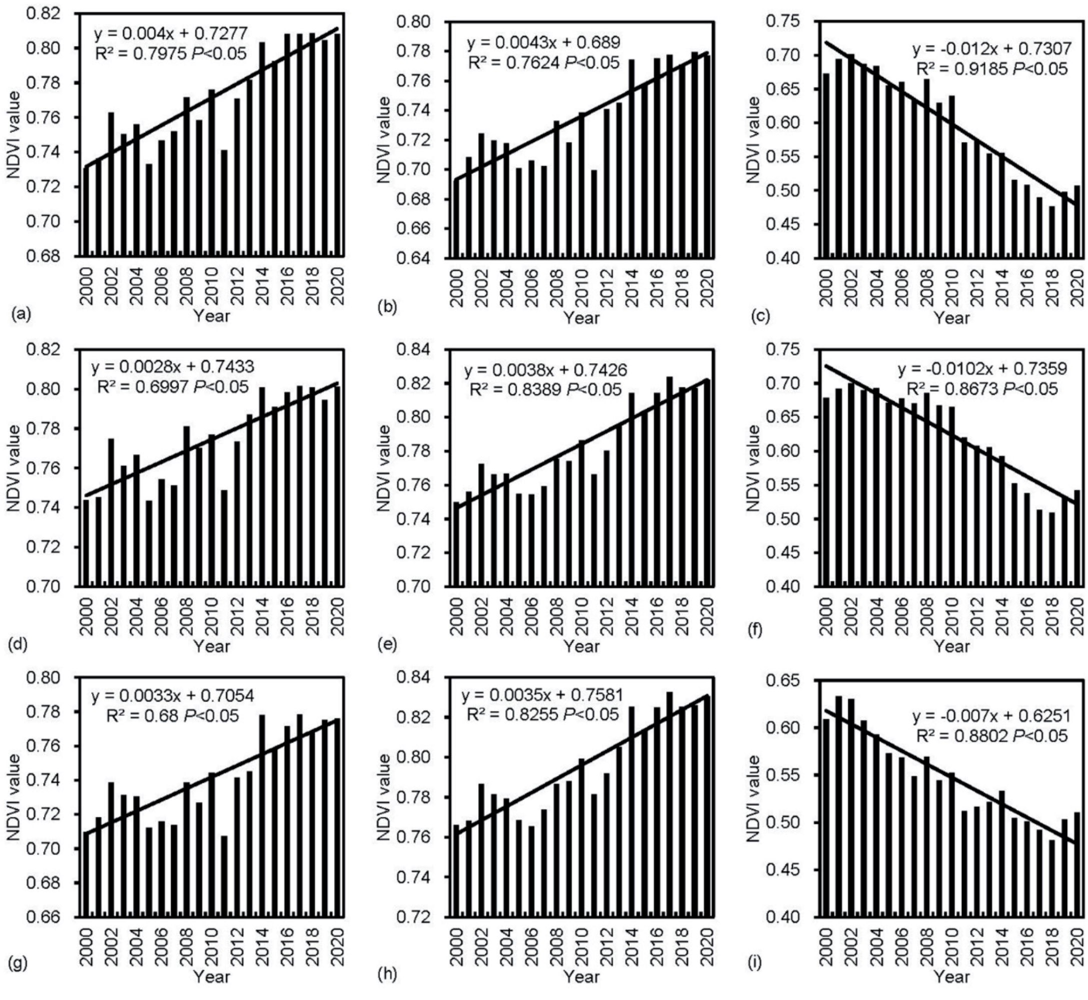

Fig. 7. Temporal variations in the NDVI values of areas where cultivated land was converted to a) forest, b) grassland, and c) constructed area; temporal variations in the NDVI values of areas where forests were converted to d) cultivated land, e) grassland, and f) constructed area; temporal variations in the NDVI values of areas where grassland was converted to g) cultivated land, h) forest, and i) constructed area in Guizhou Province from 2000 to 2020.

area over the 2000-2020 period were selected to further explore the variations in the NDVI values (Fig. 7 and Fig. 8). The results showed higher NDVI values in areas where land cover types were converted into forest than those converted to cultivated land or grassland. Moreover, the areas converted to constructed area exhibited the lowest NDVI values.

The results revealed significant temporal increasing trends of NDVI values from 2000 to 2020 in Guizhou Province, particularly in areas of conversion from cultivated land to forest and grassland, from forest to cultivated land and grassland, and from grassland to cultivated land and forest. Specifically, the conversion rates of cultivated land to forest and grassland, forest to cultivated land and grassland, and grassland to cultivated land and forest were 0.0040 ($P<0.05$) (Fig. 7a)), 0.0043 ($P<0.05$) (Fig. 7b)), 0.0028 ($P<0.05$) (Fig. 7d)), 0.0038 ($P<0.05$) (Fig. 7e)), 0.0033 ($P<0.05$) (Fig. 7g)), and 0.0035 per year ($P<0.05$) (Fig. 7h)), respectively. In contrast, areas where cultivated land, forest, and grassland were converted to constructed area exhibited significant linear decreasing trends, with changing rates of -0.0120 (Fig. 7c)), -0.0102 (Fig. 7f)), and -0.0070 per year (Fig. 7i)), respectively. In addition, the decreasing rate of NDVI values in areas converted to constructed area was more than twice the above-mentioned increasing rates. It can therefore be suggested that grassland restoration, characterized by rapid NDVI growth, contributed to the short-term improvement of vegetation in Guizhou Province, while forest restoration, as the dominant land cover type contributing to NDVI, was more beneficial to the long-term regional vegetation ecosystem. Furthermore, it is crucial to implement strict management and control policies in order to mitigate the negative impacts of human activities on the vegetation ecosystem of the study area.

The differences in the NDVI values of areas where the cultivated land, forest, and grassland were mutually

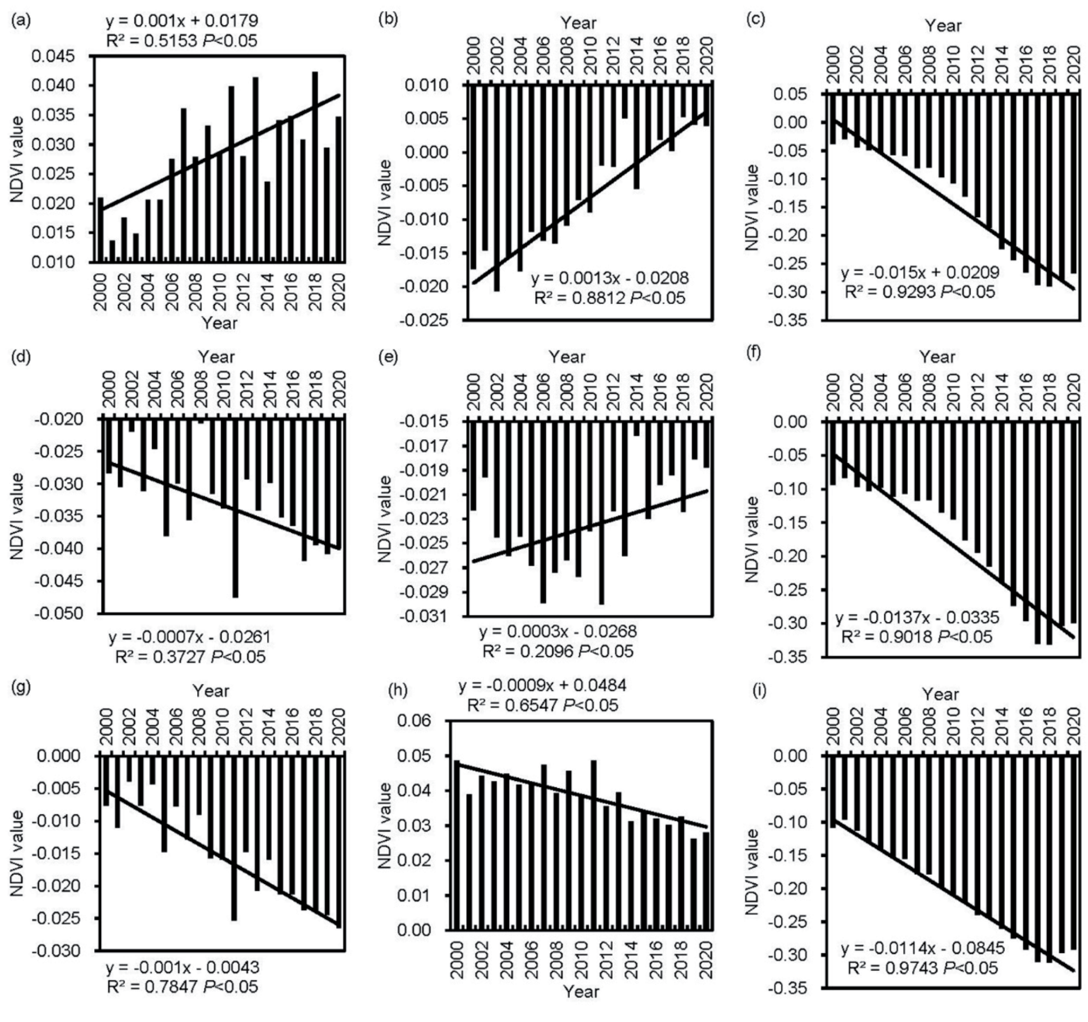

Fig. 8. Variations in the differences between the NDVI of areas where cultivated land was converted to a) forest, b) grassland, and c) constructed area; variations in the differences between the NDVI of areas where forests were converted to d) cultivated land, e) grassland, and f) constructed area; variations in the differences between the NDVI of areas where grassland was converted to g) cultivated land, h) forest, and i) constructed area.

Note: All variation trends were compared with the mean annual NDVI values of the cultivated land, forest, and grassland in Guizhou Province from 2000 to 2020.

converted from 2000 to 2020 were further compared with the mean annual NDVI of the same land cover type before the occurrence of the conversion (Fig. 8).

The differences between the mean annual NDVI values of areas converted from cultivated land and grassland to forest and the corresponding mean annual NDVI values of cultivated land and grassland were both positive, showing significant linear increasing trends, with changing rates of 0.0010 (P<0.05) (Fig. 8a)) and 0.0009 (P<0.05) (Fig. 8h)) per year, respectively. These findings indicate an improvement in vegetation coverage in the study area following the conversion of cultivated land and grassland to forest. The differences between the mean annual NDVI values of areas where cultivated land was converted to grassland, and the mean annual NDVI of cultivated land were negative and positive in the 2000-2016 and 2016-2020 periods, respectively. Overall, this finding showed that the declining trend was significantly weakened, with a changing rate of 0.0013 per year (P<0.05) (Fig. 8b)). On the other hand, the difference between the mean annual NDVI values of areas where forests were converted to grassland and the mean annual NDVI values of forests was negative. Nevertheless, this difference showed a significantly slowed decline, with a changing rate of 0.0003 per year (P<0.05) (Fig. 8e)).

The differences between the mean annual NDVI values of areas where forest and grassland were converted to cultivated land and the mean annual NDVI values of forest and grassland were all negative. The differences for areas where cultivated land, forest, and grassland were converted to constructed area were also negative. These conversions might, therefore, reduce the provincial vegetation coverage in Guizhou Province, showing significant linear decreasing trends. Indeed, changing rates of forest and grassland converted to cultivated land, and those of the cultivated land, forest, and grassland to constructed area, were -0.0007 (P<0.05) (Fig. 8d)), -0.0001 (P<0.05) (Fig. 8g)), -0.0150 (P<0.05) (Fig. 8c)), -0.0137 (P<0.05) (Fig. 8f)), and -0.0114 (P<0.05) (Fig. 8i)) per year, respectively.

The expansion of the constructed area may lead to a rapid decline in vegetation coverage of the study area, reaching a declining rate more than ten times that of the expansion of cultivated land. However, due to the small coverage area of the constructed area, its contribution to the overall variations in vegetation coverage of Guizhou Province was relatively small. Since cultivated land accounted for one-third of the provincial area, controlling the conversion of the forest and grassland to cultivated land was conducive to improving the provincial vegetation coverage level and the stability of the vegetation ecosystem in the study area.

Overall, the implementation of GGP and CCPRD has promoted the conversion of cultivated land, bare land, and other land types into forest and grassland. While reducing soil erosion and mitigating rocky desertification, the increase in forest and grassland areas has led to a rise in NDVI, resulting in an overall improvement in vegetation in Guizhou Province. Controlling the occupation of forest and grassland by urban expansion and increasing urban green space construction can also improve vegetation coverage.

Conclusions

(1) The NDVI in Guizhou Province showed a significant linear increasing trend over the 2000-2020 period, with a changing rate of 0.0033 per year (P<0.05). Spatially, the NDVI values exhibited an increasing trend, accounting for 92.23% of the total provincial area. Areas with significant increasing and decreasing trends accounted for 75.16% and 2.70% of the total provincial area, respectively. The decreasing trends of the NDVI values were concentrated in areas surrounding cities, such as Guiyang, the provincial capital.

(2) The mean annual air temperature and annual precipitation in Guizhou Province showed increasing trends from 2000 to 2020. The NDVI values were positively correlated with mean annual air temperature and annual precipitation in 79.12% and 80.44% of the total provincial area, respectively. In particular, areas with significant positive correlations between NDVI values and mean annual air temperature and annual precipitation accounted for 19.15% and 13.38% of the total provincial area, respectively. These significant correlations were mainly observed in the western, southwestern, and central regions, as well as in the eastern region, of the study area.

(3) Forests were the major land cover type in promoting vegetation coverage in Guizhou Province, followed by grassland. The NDVI values of areas converted to constructed area exhibited a significant linear decreasing trend over time, which was more than twice the increasing rate of NDVI in areas where mutual conversion of cultivated land, forest, and grassland was observed. Additionally, the results revealed significant decreasing trends in the differences between the initial mean annual NDVI values and those of areas where forest/grassland and cultivated land/forest/grassland were converted to cultivated land and constructed area, respectively. Moreover, the changing rate of areas converted from cultivated land/forest/grassland to constructed area was more than ten times higher than that of areas converted to cultivated land.

Climate warming and increased humidity have provided favorable external conditions for vegetation improvement in Guizhou Province. In addition, the implementation of ecological construction and restoration projects, such as GGP and CCPRD, has contributed to the continuous improvement of provincial vegetation conditions. From the perspective of vegetation restoration, future ecological governance in Guizhou Province should adopt a combination of arbor forests, shrubs, and grasslands. This approach can not only meet the demand for rapid vegetation restoration in the short term but also support the long-term healthy development of vegetation. At the same time, strong measures should be taken to control the rapid expansion of urban areas and the scale of cultivated land reclamation. During urban expansion, the construction of urban green spaces should be strengthened to improve vegetation coverage in built-up areas.

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Conflict of Interest

The authors declare no conflict of interest.

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