Front. Earth Sci. 2021, 15(1): 167–183
https://doi.org/10.1007/s11707-020-0842-0

RESEARCH ARTICLE

Vegetation dynamics and its response to driving factors in typical karst regions, Guizhou Province, China

Xiaocha WEI[1], Qiuwen ZHOU (✉)[1], Ya LUO[1], Mingyong CAI[2], Xu ZHOU[1], Weihong YAN[1], Dawei PENG[1], Ji ZHANG[1]

1 School of Geography and Environmental Science, Guizhou Normal University, Guiyang 550025, China
2 Satellite Environment Center of MEP, Beijing 100094, China

Abstract Analyzing the vegetation dynamics and its response to driving factors provides a vital reference for understanding regional ecological processes and ecosystem services. However, this issue has been poorly understood in karst areas. Taking Guizhou Province as a case study, based on the Normalized-Difference Vegetation Index of the Global Inventory Modeling and Mapping Studies and on meteorological data sets during 1982–2015, we evaluated vegetation dynamics and its response to climatic factors and human activities. We used several methods: the Mann–Kendall test, rescaled range analysis, partial correlation analysis, and residual analysis. The results are as follows: 1) the mean annual Normalized-Difference Vegetation Index was 0.46 and exhibited a significant increasing trend with a variation rate of 0.01/10a during 1982–2015 in Guizhou Province. The vegetation cover showed was spatially heterogeneous: High vegetation cover was distributed mainly in the center and western margin of the study area, while the other parts of the study area mainly distributed with low vegetation cover, although the vegetation cover was higher in the non-karst areas than in the karst areas; 2) in general, the climate was getting warmer and drier in Guizhou Province during 1982–2015. Vegetation cover was positively correlated with temperature and negatively correlated with precipitation. Compared to precipitation, temperature was the dominant climatic factor impacting vegetation dynamics; 3) large-scale ecological restoration projects have obviously increased vegetation cover in Guizhou Province in recent years. The contribution of human activities to vegetation changes was 76%, while the contribution of climatic factors was 24%. In summary, compared to natural forces such as climatic factors and geographic parameters, human activities were the main factor driving the vegetation dynamics in Guizhou Province.

Keywords vegetation dynamics, climate change, human activities, karst area

1 Introduction

Owing to the separate or joint effects of natural and anthropogenic causes, the terrestrial ecosystems are strongly changing at various spatial and temporal scales (Theurillat and Guisan, 2001; Hill and Donald, 2003; Martínez and Gilabert, 2009). Vegetation could be viewed as one indicator of terrestrial ecosystem conditions, and its dynamic changes can reflect variation in land use/land cover to a certain extent (Beerling et al., 1997; Liu et al., 2011; Mata González et al., 2012).

Field surveys can generate accurate information on vegetation dynamics and its drivers, but in situ observations are costly, time-consuming, and spatially limited. Since the 1980s, satellite remote sensing has been an important data source widely used for monitoring vegetation dynamics from regional to global scales (Tong et al., 2017), particularly for the Northern Hemisphere (most notably for North America and China) and Africa (Ichii et al., 2002; Ji and Peters, 2003; Piao et al., 2006; Pouliot et al., 2009; Hu et al., 2011). In general, most previous studies have reported that satellite data showed increasing vegetation cover. Apart from climatic factors, human activities are the key drivers influencing the so-called Greening Earth and accounting for the marked variation in Normalized-Difference Vegetation Index (*NDVI*) data sets (Davenport and Nicholson., 1993; Tourre et al., 2008; Pouliot et al., 2009; Zhong et al., 2010; Chen et al., 2019). However, the mechanisms and extent of influence on vegetation change are still poorly understood; because the

Received December 2, 2019; accepted October 8, 2020

E-mail: zouqiuwen@163.com

interactions of temperature, precipitation, and human activities are complex and vary across the world (Ni, 2011; Song and Ma, 2011), there has been a particular need for further research in karst areas.

Karst areas are typical and fragile ecosystems, which are concentrated mainly in eastern North America, south-central Europe, and southwestern China and account for 12%–15% of the total global land area (Wang et al., 2004). In the karst areas of southwestern China, the environment is extremely fragile and is commonly characterized by mountainous areas of carbonate rock with limited soil and low vegetation coverage and limited surface-water resources; they also tend to be overpopulated and characterized by a backward economy (Xiong et al., 2012). From the impact of the karst geomorphology and high population density, such areas eventually suffer from serious soil erosion and land degradation in the form of karst rocky desertification; this has been identified as the most severe ecological problem threatening local sustainable development (Wei et al., 2011; Tong et al., 2017). To alleviate such severe rocky desertification and improve local ecological conditions, national and local governments have implemented several ecological restoration projects (ERPs) since the late 1990s, including the Natural Forest Protection Project, the Grain for Green Project, and the Karst Rocky Desertification Comprehensive Control and Restoration Project (Tong et al., 2017). According to previous studies, areas of rocky desertification in south-western China generally decreased by 7.4%, and those that had undergone severe rocky desertification decreased by 41.3%. These remarkable results demonstrated that the vegetation cover for much of this area has been improved to some degree (Jiang et al., 2014; Brandt al., 2018; Zhou et al., 2018). In addition, karst areas of south-western China, whose climate is mostly subtropical monsoon, exhibit a notably high degree of landscape heterogeneity. As a result, vegetation changes were not only driven by climate change but complexly influenced by human activities. Because the combined effects led to high spatial heterogeneity, analyzing the relationship between vegetation change and its driving factors could provide a vital reference for understanding the instability of karst ecological systems and considerations for their protection.

Many researchers have studied vegetation dynamics and its response to driving forces in karst areas of south-western China (Wang and Yang, 2006; Meng and Wang, 2007; Zheng et al., 2009; Gao et al., 2012; Zhang et al., 2017). All these studies found that climate change and the implementation of ecological recovery projects have greatly affected vegetation cover in this region (Cai et al., 2014; Tong et al., 2016, 2017 and 2018). However, vegetation dynamics and its response to driving factors have been poorly understood, and most of the remote-sensing data sets consist of past data that does not adequately reflect the latest vegetation status in this area. Also, time-series analysis based on a short period commonly does not meet the requirements of covering both present and past vegetation dynamics in relation to ERPs, and the trends are usually not linear over a long period (Tong et al., 2017). Therefore, current time-series data covering a longer period would help to accurately elucidate the relationship between vegetation changes and their driving factors. Too, we still need comprehensive assessments of vegetation dynamics using long-period remote-sensing data sets and a variety of statistical-analysis methods. Most importantly, in previous studies, the contributions of climatic factors and human activities to vegetation dynamics in karst areas were not made clear, although they are of considerable importance for understanding regional ecological processes and ecosystem services.

Guizhou Province includes the most-concentrated distribution of karst terrain in south-western China, and it is one of the three areas worldwide with the highest concentration of karst features (Wang, 2002; Xiong et al., 2012). By background, this is a region of typically fragile ecosystems that has a subtropical moist monsoon climate and experiences notable soil erosion, karst rocky desertification, and corresponding poverty (Wang et al., 2003). Researchers have recently reported that this region has experienced dramatic land-use/land-cover change along with increased vegetation cover, while the relationship between vegetation dynamics and its response to driving factors has remained unclear (Meng and Wang, 2007; Zheng et al., 2009; Gao et al., 2012; Tong et al., 2017, 2018; Liao et al., 2019; Zhang et al., 2019). Therefore, to investigate this relationship, we took the typical karst region in Guizhou Province as a case study. Basing our research on the *NDVI* of the Global Inventory Modeling and Mapping Studies (GIMMS) and temperature and precipitation data during 1982–2015, we applied various methods: time-series trend analysis, the Mann–Kendall test, rescaled range analysis, partial correlation analysis, and residual analysis. The objectives of our study were to investigate the spatiotemporal-variation characteristics of the vegetation cover and climate in Guizhou Province; to analyze correlations between vegetation cover and climatic factors; and to quantitatively separate the contributions of climatic factors and human activities to vegetation change. The results of this study not only contribute to understand the relationship between vegetation dynamics and its driving factors in Guizhou Province, but also is proposed to be of high relevance for evaluating the effectiveness of ERPs and to provide a scientific basis for further vegetation-restoration practices in karst areas.

2 Materials and methods

2.1 Study area

Guizhou Province, which is in the center of south-western

China (24°37′–29°13′N, 103°36′–109°35′E), covers an area of 176000 km^2; karst areas comprise 64.2% of the province (Fig. 1). The altitudes range within 156–2885 m (averaging ~1100 m), generally decreasing from east to west but with a high degree of landscape heterogeneity. We divided the study area into six landform types based on topography, lithology, and geology (Yuan et al., 2014; Tong et al., 2017). Guizhou Province has a typical mild, subtropical humid monsoon climate with a mean annual temperature of 15°C and mean annual precipitation of 1200 mm that mainly occurs during April–September. The dominant forest types are subtropical evergreen (needle and broad leaf), deciduous broadleaf, and mixed forests (Cai et al., 2014).

2.2 Data sets

2.2.1 Global inventory modeling and mapping studies Normalized-Difference Vegetation index

The GIMMS *NDVI* data were obtained from the US National Aeronautics and Space Administration Goddard Space Flight Center (available at NASA website). Compared with the Pathfinder Advanced Very High Resolution Radiometer (AVHRR) land data set, the negative effects of calibration, geometry, viewing angle, and volcanic aerosols have been eliminated in the GIMMS *NDVI* data set, which has been reported to be one of the best data sets available for large-scale vegetation-dynamics studies, not only because of its relative continuity in spatiotemporal terms, but also owing to its significant correlations with some vegetation parameters, such as net primary production, leaf area index, and the fraction of photosynthetically active radiation absorbed by the vegetation canopy (Liu et al., 2011).

In this study, the GIMMS *NDVI* data set for the period of 1982–2015 was used to evaluate the vegetation-cover change in Guizhou Province. The original data had a 15-day temporal resolution and an 8 km × 8 km spatial resolution; we converted the data into the GeoTIFF format by using matrix laboratory (MATLAB) software with Albers equal-area conic projection and the WGS-84 ellipsoid. The annual *NDVI* image was calculated from monthly *NDVI* using the maximum-value composites method (Zhang et al., 2019), which not only can further reduce atmospheric interference and satellite orbit drift but also can modify the effect of the sun's altitude or angle. Moreover, it has been widely used to evaluate vegetation dynamics from regional to global scales. To verify the accuracy of the GIMMS *NDVI*, we established the regression equation between the GIMMS *NDVI* (2000–2015) data set and the Moderate-Resolution Imaging Spectroradiometer (MODIS) *NDVI* (2000–2015) data set, which has a higher spatial resolution (1 km × 1 km). The

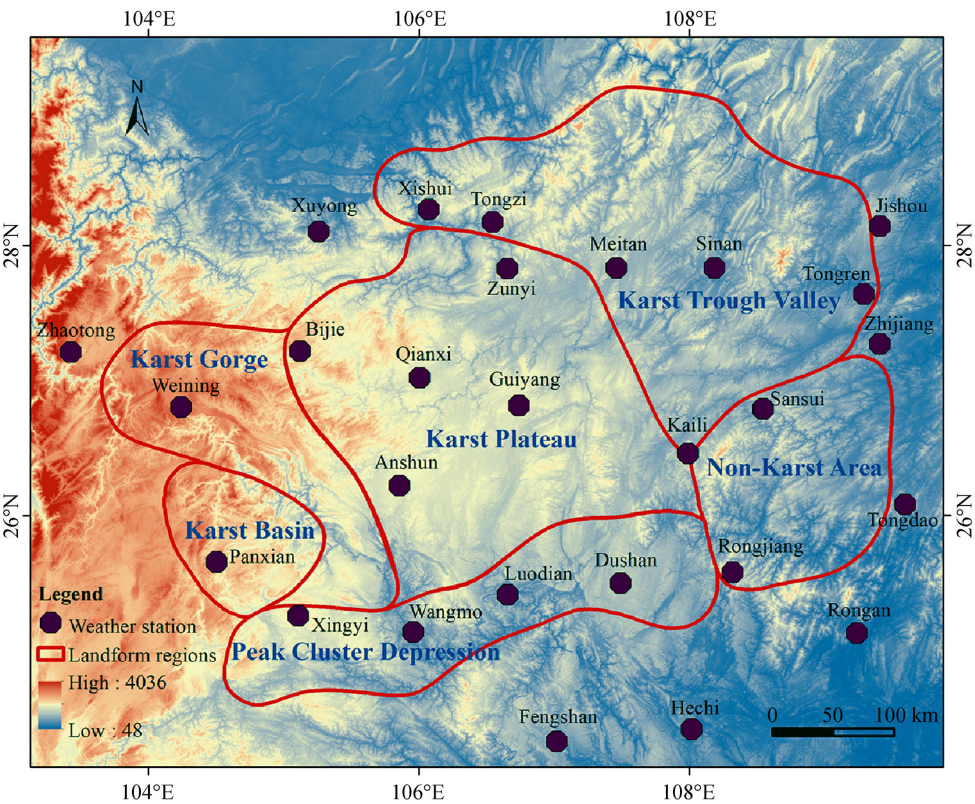


Fig. 1 Study-area location, altitudes, landform regions, and weather-station distribution.

resulting equation, $Y_{MODIS\ NDVI} = 0.8566X_{GIMMS\ NDVI} - 0.0408$ ($R^2 = 0.4833$), surpassed the 0.05 significance level. Using Google Earth software, we also found that the *NDVI* value was consistent with the actual distribution of vegetation cover in the study area. Therefore, we used GIMMS *NDVI* data to evaluate the vegetation dynamics in this study.

2.2.2 Meteorological data

Monthly precipitation and temperature were downloaded directly from the China Meteorological Science Data Sharing Service Network (available at CMA website). We used the Inverse Distance Weighting interpolation method, the hypothesis of which is that all attribute values for a geographic surface extent are interrelated, but the closer values are more strongly related than are the more-distant ones. Many previous studies conducted in Guizhou Province demonstrated that this is the optimal interpolation method for this region (Zhou et al., 2018; Liao et al., 2019). We used ArcGIS software with this interpolation method to obtain the spatial temperature and precipitation data set at a resolution of 8 km × 8 km. We input monthly climate data from 19 standard meteorological stations within Guizhou Province, and, to improve the interpolation precision of the climatic factors, we also incorporated data from 8 other standard meteorological stations (Zhaotong, Xuyong, Jishou, Zhijiang, Tongdao, Rongan, Hechi, and Fengshan) in the nearby surrounding area (Fig. 1). Then we calculated mean annual temperature and precipitation from these monthly data.

2.3 Methods

2.3.1 Linear regression trend analysis

We used linear regression analysis to effectively simulate the vegetation-variation trends for each grid and to comprehensively reflect spatial-variation characteristics of vegetation cover in the study area. The variation slope of the annual NDVI images for each pixel was determined by using the Interactive Data Language program. Variation trends were classified into three types: increasing (slope > 0), decreasing (slope < 0), stable (slope = 0) (Liu et al., 2011; Tong et al., 2016 and 2017).

2.3.2 Mutation detection

Using the method and detailed algorithms of the Mann–Kendall test (Wang et al., 2013) and MATLAB programs, we tested the variation mutations of annual *NDVI*, temperature, and precipitation. By analyzing the order curve (*UF*) and the reverse order curve (*UB*), we can know the variation trend of the variables. If the *UF* and *UB* curves intersect within the critical curve, the moment at which the intersection occurs is the beginning of the mutation (change point). If $UF > 0$, it represents the variable exhibiting an increasing trend; if $UF < 0$, it represents the variable exhibiting a decreasing trend. If *UF* exceeds the critical curve, the variation trend is significant. The value of the critical curve (±1.96, if $|UF| > 1.96$ or $|UB| > 1.96$) represents the variation trend exceeding the significance level.

2.3.3 Rescaled range analysis

Using the rescaled range analysis method (Cao et al., 2013) and Interactive Data Language programming, we derived the variation trend for *NDVI* and calculated temperature and precipitation. If the Hurst index $H = 0.5$, the variation trend is not affected by that of the past; if $H > 0.5$, it indicates that the variation trend has persistent characteristics, and the future variation trend is expected to be consistent with that of the past; and if $H < 0.5$, it indicates the future variation trend is contrary to that of the past. The closer the index is to $H = 1$, the more persistent the sequence, and the closer to $H = 0$, the less persistent the sequence. Cao et al. (2013) provided detailed algorithms of the rescaled range analysis method.

2.3.4 Partial correlation analysis of Normalized-Difference Vegetation Index and climatic factors

Geographic systems are complex and involve various interdependent factors; a change in one of these factors will influence the others. Partial correlation analysis is often used to determine the relationship between two variables and when that could override the influence of a third factor (Zhang et al., 2011). A partial correlation coefficient (*R*) is in the range $-1 < R < 1$. When $R = 0$, it means that the two variables are not correlated; the closer its value is to $R = -1$, the stronger the negative correlation, and the closer to $R = 1$, the stronger the positive correlation. We used the *t*-test method to determine the significance of the partial correlation coefficient.

2.3.5 Residual analysis

To alleviate the severe rocky desertification and lessen the ecological degradation in the karst areas of southwestern China, the national and local Chinese governments have implemented a series of ERPs since the late 1990s (Tong et al., 2017). These ERPs were mostly initiated since 1999. Vegetation will not exhibit obvious recovery until its second or third year. For the present study, we divided the *NDVI* data for the entire study period into a reference period (1982–2001) and a conservation period (2002–2015). The reference period we characterized as a baseline when vegetation was not strongly affected by human activities, whereas the conservation period was characterized by vegetation changes resulting from obvious human effort.

The residual method was applied to separate vegetation changes initiated by human activities from changes due to climatic factors (Evans and Geerken, 2004; Jiang et al., 2017; Ma et al., 2017). We applied multiple correlation regression analysis between monthly *NDVI* (as the response variable) and monthly climate factors (temperature and precipitation as predictors) for the reference period (1982–2001). Because the land-surface conditions (such as geomorphology, hydrology, soil, and land-use/land-cover types) may influence the relationship between *NDVI* and climatic variables, and this influence is particularly obvious in karst areas characterized by high spatial heterogeneity, we established the multiple correlation regression for each land-cover type and calculated it for each pixel. Then, if the correlation coefficient of the *NDVI*–climate regression model achieved the significance level of 0.05, we used this regression model to predict *NDVI* for the conservation period 2002–2015. Tong et al. (2017) and Zhang et al. (2019) identified the contributions of climatic factors and human activities to vegetation change by the slopes of the predicted and residual *NDVI* on observed *NDVI*. The specific algorithms used in the residual analysis are as follows:

$$NDVI_{(i,t)} = a \times T_{(i,t)} + b \times P_{(i,t)} + C, \quad (1)$$

$$NDVI_{\text{residual}} = NDVI_{\text{observed}} - NDVI_{\text{predicted}}, \quad (2)$$

$$C_{\text{c}(i,t)} = \text{slope}(NDVI_{\text{predicted}(i,t)})/\text{slope}(NDVI_{\text{observed}(i,t)}) \times 100\%, \quad (3)$$

$$C_{\text{h}(i,t)} = \text{slope}(NDVI_{\text{residual}(i,t)})/\text{slope}(NDVI_{\text{observed}(i,t)}) \times 100\%, \quad (4)$$

where $NDVI_{(i,t)}$ is *NDVI* for month t at pixel i; $T_{(i,t)}$ is temperature for month t at pixel i; $P_{(i,t)}$ is precipitation for month t at pixel i; a and b are regression coefficients; c is a constant; $NDVI_{\text{observed}}$ is observed *NDVI*, $NDVI_{\text{predicted}}$ is predicted *NDVI*, and $NDVI_{\text{residual}}$ is residual *NDVI*. When $NDVI_{\text{residual}} > 0$, it means that human activities do positively impact vegetation variation; when $NDVI_{\text{residual}} < 0$, it means that human activities do negatively impact vegetation variation; when $NDVI_{\text{residual}} = 0$, it means that human activities have no impact on vegetation variation. $C_{c(i,t)}$ is climatic factors' contribution to vegetation change, and $C_{\text{h}(i,t)}$ is human activities' contribution to vegetation change.

3 Results

3.1 Spatiotemporal-variation characteristics of Normalized-Difference Vegetation Index

The mean annual *NDVI* was 0.46 during 1982–2015 in Guizhou Province (Fig. 2(a)), and it exhibited a significant increasing trend with a variation rate of 0.01/10a ($R^2 = 0.52$, $n = 34$, $\alpha < 0.1$). It increased slightly during 1982–1999, clearly decreased during 1999–2000, and then increased through 2015. Overall, the mean annual *NDVI* was low during 1982–2004 and high during 2004–2015. The results showed that vegetation cover had improved, indicating that vegetation restoration was succeeding in Guizhou Province during 1982–2015 and was particularly apparent in the last part of that period.

The annual *NDVI* by landform ranged from highest to lowest in the following order: Non-Karst Area > Karst Basin > Karst Plateau > Karst Trough Valley > Karst Gorge and Peak Cluster Depression (Fig. 2(b)). The index ranged 0.40–0.53 in the Non-Karst Area, Karst Basin, and Karst Plateau; was 0.35 in the Karst Trough Valley; and was 0.28 in the Karst Gorge and Peak Cluster

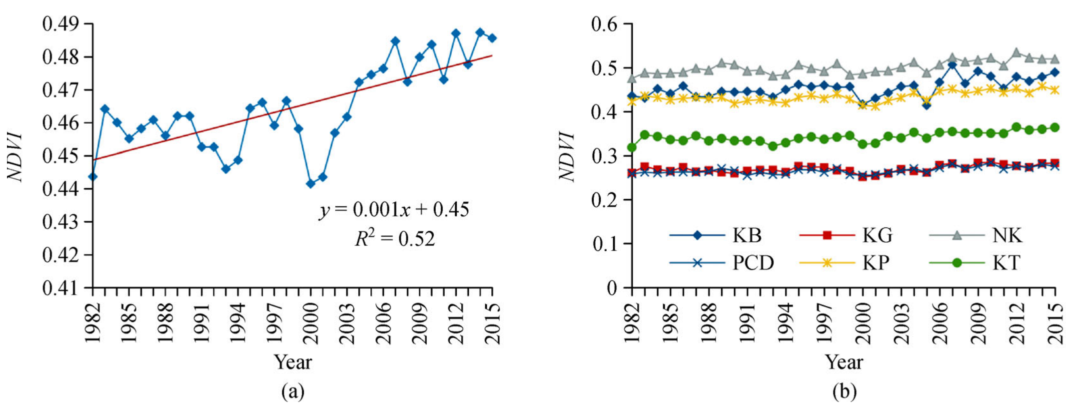


Fig. 2 Temporal variation of annual *NDVI* for entire study area (a) and for each landform region (b) in Guizhou Province during 1982–2015. (KB—Karst Basin; KG—Karst Gorge; KP—Karst Plateau; KT—Karst Trough Valley; *NDVI*—Normalized-Difference Vegetation Index; NK—Non-Karst Area; PCD—Peak Cluster Depression)

Depression. The monthly NDVI (Fig. 3) ranged 0.38–0.44 during June–October and was ~0.33 during April–May and November. The lowest *NDVI*, ranging 0.26–0.31, occurred during December–March.

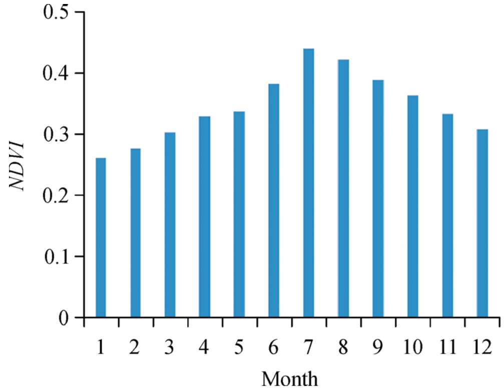


Fig. 3 Monthly Normalized-Difference Vegetation Index (*NDVI*) for Guizhou Province during 1982–2015.

The vegetation cover showed high spatial heterogeneity in Guizhou Province (Fig. 4(a)). The proportions of medium and high vegetation cover were greater than those of low and very high vegetation cover, while very low vegetation cover was rare in the study area. Vegetation cover apparently also differed by landform (Fig. 4(b)): High and very high vegetation cover were distributed mainly in the Non-Karst Area; medium vegetation cover was mostly in the Karst Basin and Karst Gorge; and low vegetation cover was mainly in the Karst Gorge, Karst Basin, and Karst Plateau. Generally, high vegetation cover was mainly in the center and along the western margin of the province, while other areas were mainly characterized by low vegetation cover. Vegetation cover was higher in non-karst areas than in the karst areas.

During 1982–2001, vegetation degraded slightly to moderately were distributed throughout Guizhou Province (Fig. 5(a)), with less-extensive areas of vegetation that were severely degraded or were stable. Highly or moderately improved vegetation occupied a relatively small proportion of the province. In general, vegetation that was slightly or moderately degraded was distributed over the entire Guizhou Province. Notable spatial differences were observed in vegetation change in the different landform regions (Fig. 5(b)). Vegetation that was highly, moderately, or only slightly improved occurred mostly in the Karst Gorge, Peak Cluster Depression, and Karst Basin. Vegetation that was only slightly degraded occurred mainly in the Peak Cluster Depression, Non-Karst Area, and Karst Basin. Vegetation that was moderately or severely degraded was distributed primarily in the Karst Gorge, Karst Plateau, and Karst Basin.

The vegetation cover generally presented an obvious increasing trend and showed high spatial heterogeneity in Guizhou Province during 2002–2015 (Fig. 5(c)). Highly or moderately improved vegetation was distributed across most of the study area, while severely degraded vegetation was mainly in the northern margin of this region. Highly improved vegetation was mainly distributed in the Karst Trough Valley, Karst Gorge, and Karst Plateau (Fig. 5(d)). The proportions of moderately and slightly improved vegetation were similar among the different region. Generally, compared with the period of 1982–2001, the vegetation showed a more obviously increasing trend during the period 2002–2015.

During 1992–1996 and 2000–2004, $UF < 0$, and the annual *NDVI* showed a weakly decreasing trend; during other periods, $UF > 0$ but below the critical curve (Fig. 6(a)). This indicates that the annual *NDVI* exhibited a generally increasing trend in Guizhou Province during 1982–2015. In 2008, the *UF* and *UB* curves intersected at a

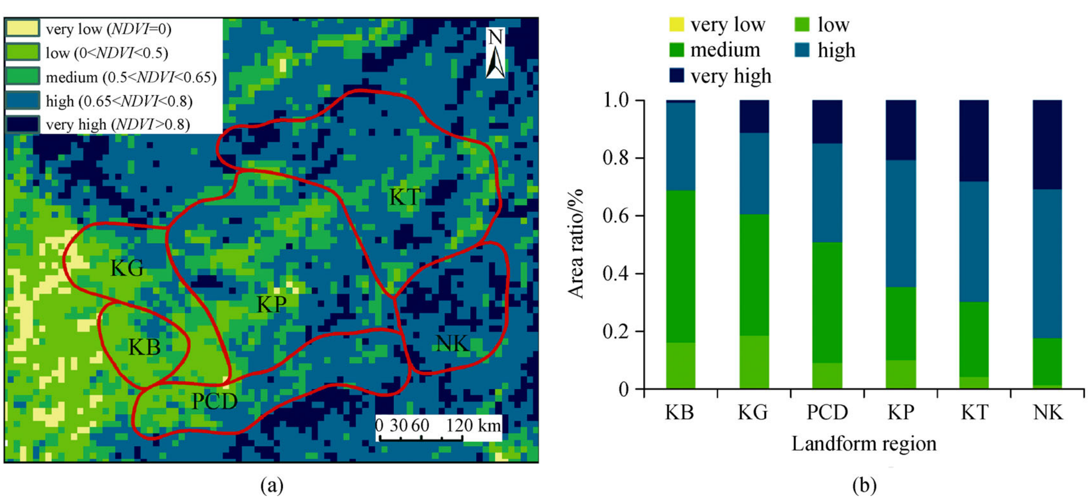


Fig. 4 Spatial distributions of vegetation cover in Guizhou Province and statistics of vegetation cover in each landform region. (KB—Karst Basin; KG—Karst Gorge; KP—Karst Plateau; KT—Karst Trough Valley; *NDVI*—Normalized-Difference Vegetation Index; NK—Non-Karst Area; PCD—Peak Cluster Depression)

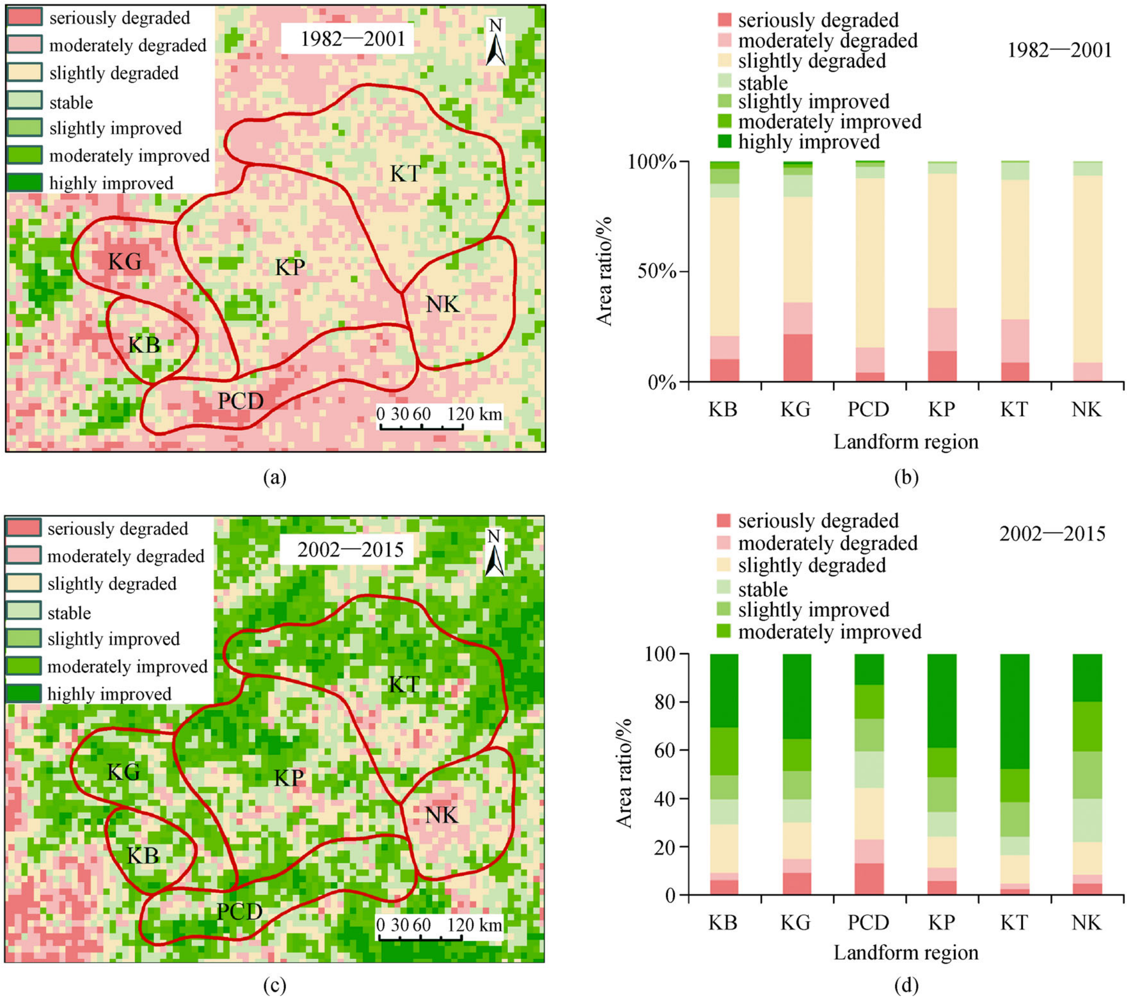


Fig. 5 Variation trends for different landform regions in Guizhou Province: (a) 1982–2001 vegetation cover and (b) area ratio; (c) 2002–2015 vegetation cover and (d) area ratio. Definitions of trends: severely degraded, slope < –0.0015; moderately degraded, –0.0015 < slope < –0.0005; slightly degraded, –0.0005 < slope < 0.001; stable, 0.001 < slope < 0.002; slightly improved, 0.002 < slope < 0.003; moderately improved, 0.003 < slope < 0.004; highly improved, slope > 0.004. (KB—Karst Basin; KG—Karst Gorge; KP—Karst Plateau; KT—Karst Trough Valley; NK—Non-Karst Area; PCD—Peak Cluster Depression)

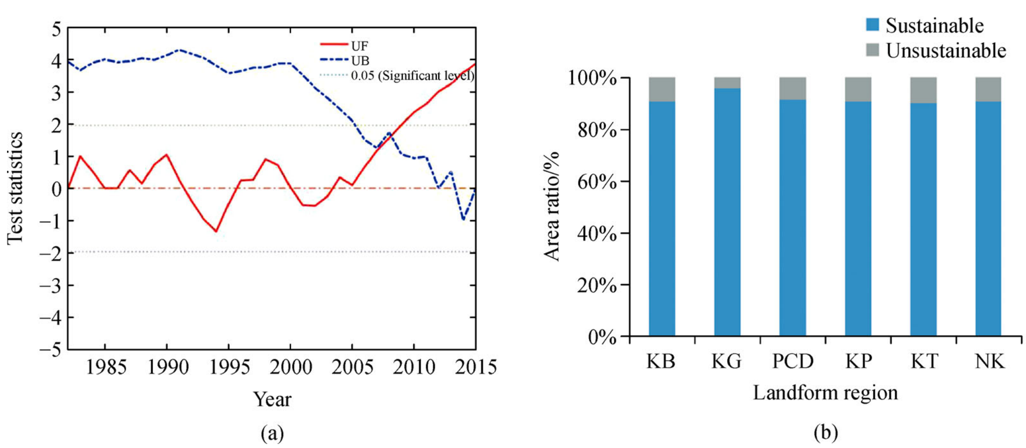


Fig. 6 (a) Mann–Kendall test of Normalized-Difference Vegetation Index for Guizhou Province during 1982–2015. (b) Expected future vegetation-variation trend (according to Hurst index) for each landform region in Guizhou Province. (KB—Karst Basin; KG—Karst Gorge; KP—Karst Plateau; KT—Karst Trough Valley; NK—Non-Karst Area; PCD—Peak Cluster Depression)

point that was within the critical curve, thereby indicating that *NDVI* mutated in that year. The *UF* exceeded the critical curve in 2009; this reflected successful implementation of several ERPs in facilitating vegetation recovery in Guizhou Province since the late 1990s and accounts for the obviously increasing trend of the annual *NDVI* apparent in recent years, particularly since 2009. *UF* also showed an unstable variation trend before 2005, but after that, it maintained a steady upward trend. This indicates that the annual *NDVI* showed fluctuating tendencies before 2005, after which it increased steadily.

Sustainable vegetation covered the greatest area in Karst Gorge (Fig. 6(b)). Among all the landform region, the proportion of sustainable vegetation was much higher than that of unsustainable vegetation, and the overall Hurst index was 0.59, the value $H > 0.5$ indicating that the vegetation cover in Guizhou Province would continue its increasing trend in the future. Also, the persistence characteristics of the change in vegetation cover did not obviously differ among the landform regions.

3.2 Spatiotemporal-variation characteristics of climatic factors

The mean annual temperature was 15.59°C during 1982–2015 in Guizhou Province; the highest temperature was 16.35°C (observed in 2013), and the lowest was 14.68°C (in 1984). Temperatures generally showed a significant increasing trend, with a variation rate of 0.231°C/10a (R^2 = 0.282, n = 34, $\alpha < 0.1$), indicating a warming trend for the climate of Guizhou Province during those 34 years. High temperatures were observed mostly in the Peak Cluster Depression, Non-Karst Area, and Karst Trough Valley, while the lower temperatures were in the Karst Basin, Karst Plateau, and Karst Gorge (Fig. 7(b)).

The annual precipitation exhibited a decreasing trend in Guizhou Province during the 34 years 1982–2015 (Fig. 8(a)), with a variation rate of –11 mm/10a (R^2 = 0.0075, n = 34, $\alpha > 0.1$). Three phases can be identified for this period: a clearly decreasing trend during 1982–1990; a stable period during 1990–2006; and a period of large fluctuations in precipitation, 2006–2015. Precipitation was in the range 818.2–1337.9 mm, spanning 519.7 mm. Heavy precipitation occurred mainly in the Karst Trough Valley, Peak Cluster Depression, and the Non-Karst Area (Fig. 8(b)); lower levels of precipitation generally occurred in the Karst Gorge, Karst Basin, and Karst Plateau within the study area.

Generally higher in the southern and eastern parts of the study area, annual temperatures decreased toward the north-west over the entire area (Fig. 9(a)). The highest temperatures were observed in Wangmo and Luodian; somewhat-lower to moderate temperatures were experienced in Congjiang, Rongjiang, Yinjiang, Jiangkou, and other areas; and the lowest temperatures occurred in Bijie, Liupanshui, and Zunyi. Minor precipitation occurred in Bijie, Weining, Qianxi, Zunyi, Tongzi, and Xishui, while other areas experienced moderate to heavy precipitation (Fig. 9(b)). Overall, annual precipitation was higher in the south-western, southern, eastern, and north-eastern parts of the study area and decreased toward the north-west. In general, the spatial distribution of *NDVI* was consistent with temperature and precipitation data for Guizhou Province.

The *UF* curve was > 0 during much of the study period, reflecting the generally increasing trend of the mean annual temperature during 1982–2015 (Fig. 10(a)). During 2006–2015, the *UF* curve exceeded the critical curve, reflecting the significant warming trend in Guizhou Province, particularly during this 10-year period. The *UF* and *UB* curves intersected in 1998, and their intersection was within the critical curve, indicating that the temperature change point occurred in 1998. The calculated Hurst index was 0.32, showing that the mean annual temperature

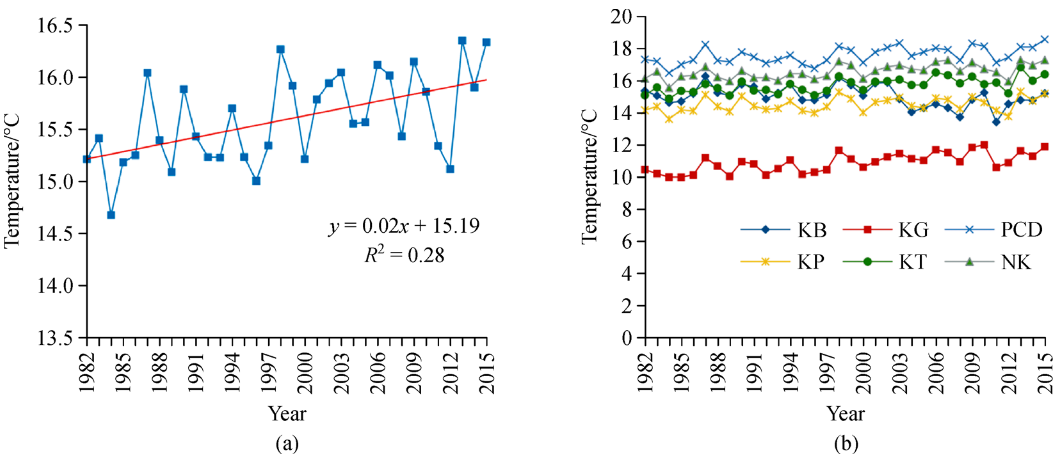


Fig. 7 Mean annual temperatures (a) for entire study area and (b) for each landform region in Guizhou Province, 1982–2015. (KB—Karst Basin; KG—Karst Gorge; KP—Karst Plateau; KT—Karst Trough Valley; NK—Non-Karst Area; PCD—Peak Cluster Depression)

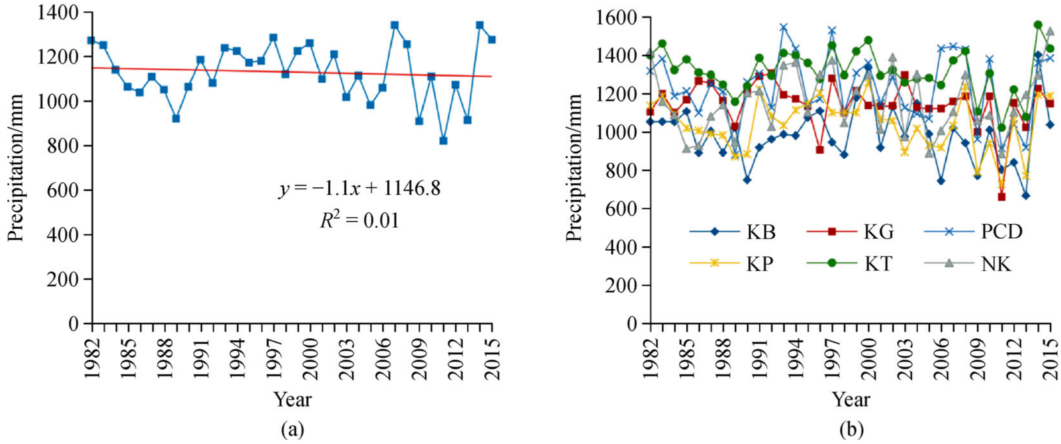


Fig. 8 Mean annual precipitation (a) for Guizhou Province and (b) for each landform region, 1982–2015. (KB—Karst Basin; KG—Karst Gorge; KP—Karst Plateau; KT—Karst Trough Valley; NK—Non-Karst Area; PCD—Peak Cluster Depression)

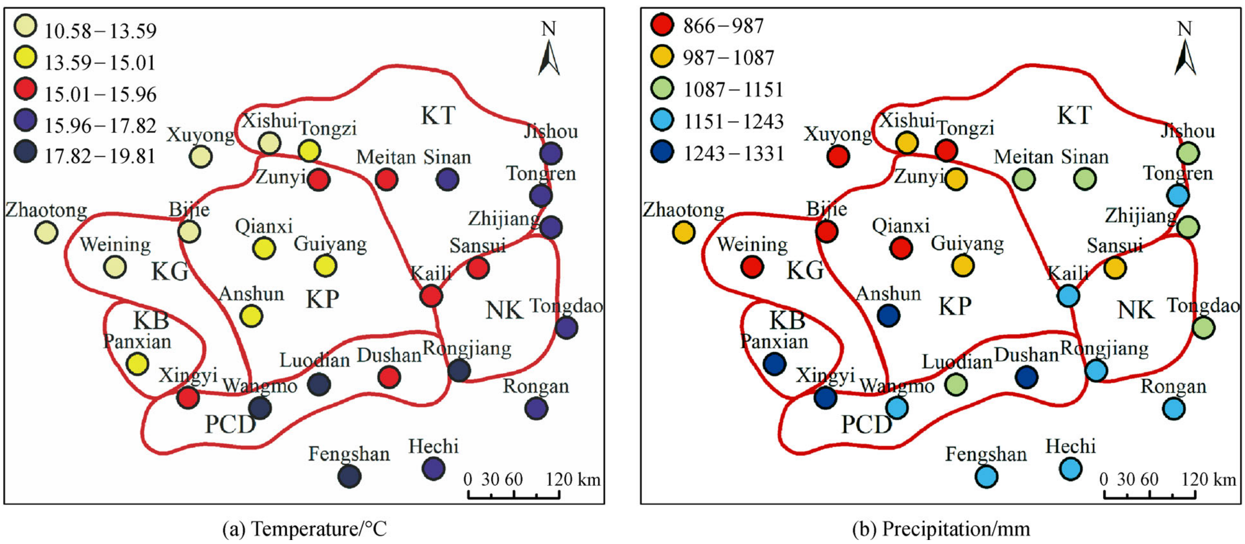


Fig. 9 Mean annual (a) temperature (°C) and (b) precipitation (mm) for Guizhou Province, 1982–2015. (KB—Karst Basin; KG—Karst Gorge; KP—Karst Plateau; KT—Karst Trough Valley; NK—Non-Karst Area; PCD—Peak Cluster Depression)

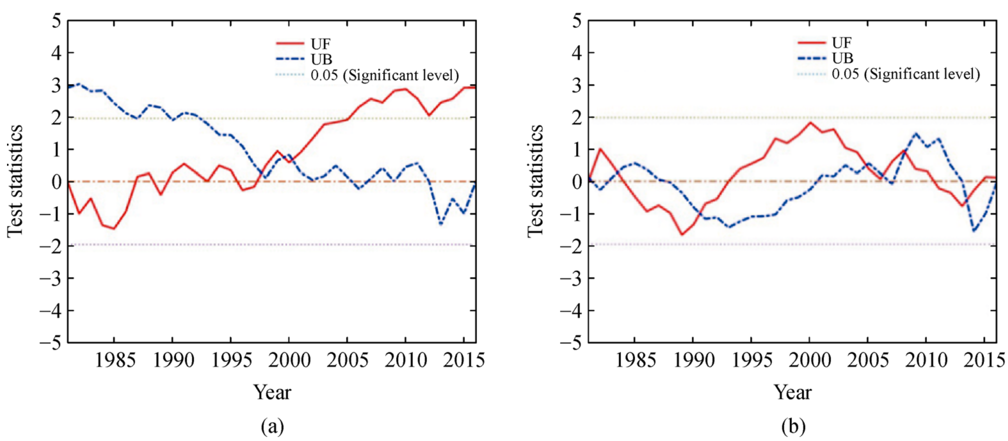


Fig. 10 Change in (a) mean annual temperature and (b) precipitation, Guizhou Province, 1982–2015.

change in Guizhou Province did not represent a persistent tendency. This meant that the temperature would follow a decreasing trend after 2015. The UF curve, generally < 0 (Fig. 10(b)), indicates that precipitation exhibited a decreasing tendency during 1982–2015. Multiple intersections of the UF and UB curves occurred over the entire study period, particularly during 2006–2015, indicating that precipitation had a tendency toward unstable variation during this period. The Hurst index was 0.45 for precipitation, which suggests that precipitation will show an increasing trend after 2015.

Monthly temperatures (Fig. 11(a)) were the highest during June–August (in the range 22.37°C–24.22°C), with peak temperatures often occurring in July; lower temperatures occurred during March–May and September–November (in the range 11.34°C–20.87°C); and the lowest temperatures occurred during December–February (in the range 5.28°C–7.40°C). The coldest period was often in January, and the difference between the highest and lowest temperatures was 18.94°C. Precipitation (Fig. 11(b)) was greatest during May–August (142.036–213.328 mm) and peaked in June. It was lower during March–April and September–November (ranging 42.734–94.807 mm), and the lowest precipitation typically occurred during December–February (in the range 21.347–26.496 mm). The difference between the maximum and minimum monthly precipitation was 191.981 mm (Fig. 11(b)). The highest monthly temperatures and greatest precipitation generally occurred in summer, moderate values occurred in spring and autumn, and the lowest values were in winter. This pattern was consistent with that of the monthly *NDVI*.

3.3 Relationship between *NDVI* and climatic variables

According to statistical data analysis (Table 1), Pearson correlation coefficients between the monthly *NDVI* and monthly temperatures during the six months January–June were 0.52, 0.523, 0.502, 0.446, 0.421, and 0.619, respectively; were small during the six months July–December; and were negative for September and October. The correlation coefficient between the annual *NDVI* and annual temperature was 0.411. Monthly *NDVI* and monthly precipitation correlated negatively during most months. *NDVI* showed stronger correlation with precipitation in summer and winter than in spring and summer, while the correlation coefficient between annual *NDVI* and annual precipitation was 0.089. Generally, the results show positive correlation between *NDVI* and temperature and negative correlation between *NDVI* and precipitation.

The spatial distribution of the correlation coefficients between mean annual *NDVI* and climatic factors (Fig. 12) indicates that the mean annual *NDVI* correlates negatively with mean annual temperature in Panxian, Anshun, and Guiyang but positively across most of the study area. The mean annual *NDVI* showed positive correlation with mean annual precipitation mainly in the eastern and northern parts of Guizhou Province, while it showed negative correlation in other parts of the study area. The mean annual *NDVI* showed positive correlation with mean annual temperature mainly in the Non-Karst Area, Karst Trough Valley, and Peak Cluster Depression, while it showed negative correlation in the Karst Gorge, Karst Plateau, and Karst Basin. Generally, the correlation

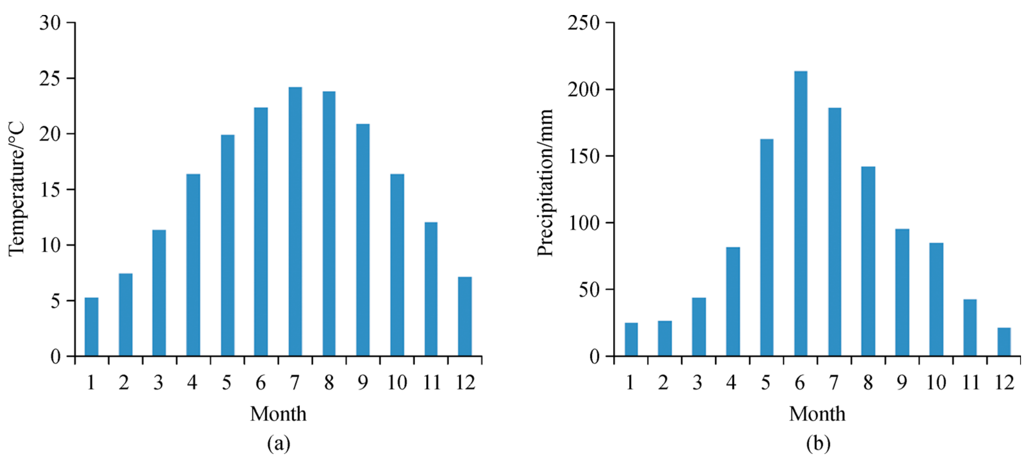
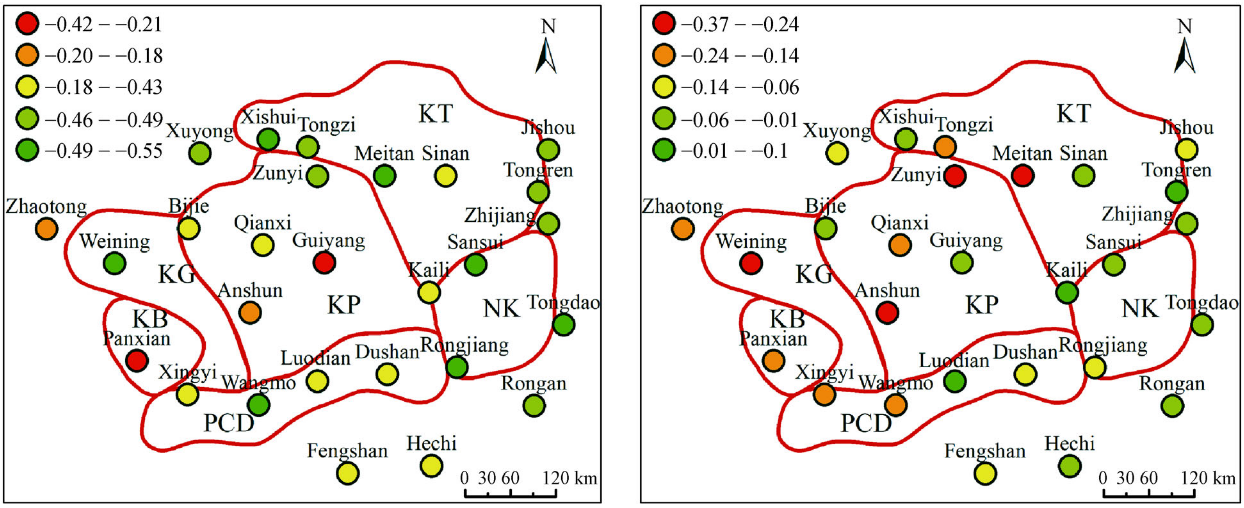


Fig. 11 (a) Monthly temperatures and (b) precipitation, Guizhou Province, 1982–2015.

Table 1 Pearson correlation coefficients between *NDVI* and temperature and between *NDVI* and precipitation

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
R_{ndvi-t}	0.552**	0.523**	0.502**	0.446**	0.421*	0.559**	0.078	0.195	−0.097	−0.094	0.081	0.209	0.411
R_{ndvi-r}	−0.151	−0.373*	0.073	0.06	0.106	−0.427*	−0.111	−0.191	0.106	0.07	−0.20	−0.028	−0.089

Notes: R_{ndvi-t} is correlation coefficient between *NDVI* and temperature, and R_{ndvi-r} is that between *NDVI* and precipitation. ** represents significant correlation at the 0.05 level, and * indicates significant correlation at the 0.1 level.



(a) *NDVI* and temperature (b) *NDVI* and precipitation

Fig. 12 Correlation coefficients between monthly (a) *NDVI* and temperature and (b) *NDVI* and precipitation at each meteorological station in Guizhou Province, 1982–2015. (KB—Karst Basin; KG—Karst Gorge; KP—Karst Plateau; KT—Karst Trough Valley; NDVI—Normalized-Difference Vegetation Index; NK—Non-Karst Area; PCD—Peak Cluster Depression)

coefficients between *NDVI* and climatic variables exhibited obvious spatial heterogeneity; they gradually decreased from east to west across the province.

3.4 Contribution of human activities and climatic factors to vegetation dynamics

Correlation analysis indicated that the *NDVI* significantly ($P < 0.05$) correlated with temperature in January or February and in June, and likewise significantly ($P < 0.05$) correlated with precipitation in February and in June during 1982–2001. Therefore, climatic factors observed in these months and *NDVI* during 1982–2001 were used to establish regression models for each land-cover type (Table 2). We used precipitation and temperature data for the corresponding months in 2002–2015 to calculate the predicted annual *NDVI* based on these models (Fig. 13(a)).

The average residual *NDVI* for the years 2002–2015 was 0.176, and residual $NDVI > 0$ values were distributed across much of the study area (Figs. 13(b) and 13(c)). Residual $NDVI < 0$ were generally distributed in the central and western parts of Guizhou Province, including Guiyang City, Anshun City, Weining County, and Xingyi City; a possible reason is that these regions experienced dramatic land-use/land-cover changes, and human activities negatively impacted the vegetation dynamics. The average contribution of human activities to vegetation change in the study area was 76%, while the contribution of climatic factors was 24% (Fig. 13(d)). In general, positive human activities had a greater impact on vegetation dynamics than negative human activities in the province during 2002–2015.

4 Discussion

4.1 Impacts of climatic factors and human activities on vegetation dynamics

The Pearson correlation coefficients between *NDVI* and climate indicate that the *NDVI* generally correlated

Table 2 Multiple correlation regressions of Normalized-Difference Vegetation Index (*NDVI*) and climatic factors.

	Regression models[a]	R^2
Cultivated land	$NDVI = -0.00022T_2 + 0.00674T_6 - 0.00012P_2 - 0.00003P_6 + 0.60125$	0.445
Forest	$NDVI = -0.00017T_1 + 0.00495T_6 - 0.0002P_2 - 0.0008P_6 + 0.64685$	0.464
Shrub	$NDVI = -0.00019T_2 + 0.00642T_6 - 0.0001P_2 - 0.00002P_6 + 0.58526$	0.465
Other woodland	$NDVI = -0.0002T_1 + 0.00457T_6 - 0.00008P_2 - 0.00005P_6 + 0.63728$	0.463
Grass	$NDVI = -0.00032T_2 + 0.00531T_6 - 0.00011P_2 - 0.000005P_6 + 0.62017$	0.444
Other	$NDVI = 0.00013T_2 + 0.00495T_6 - 0.0006P_2 - 0.00008P_6 + 0.64975$	0.444

Notes: [a] T_1, T_2, T_6: temperatures in January, February, and June; P_2, P_6: precipitation in February and June.

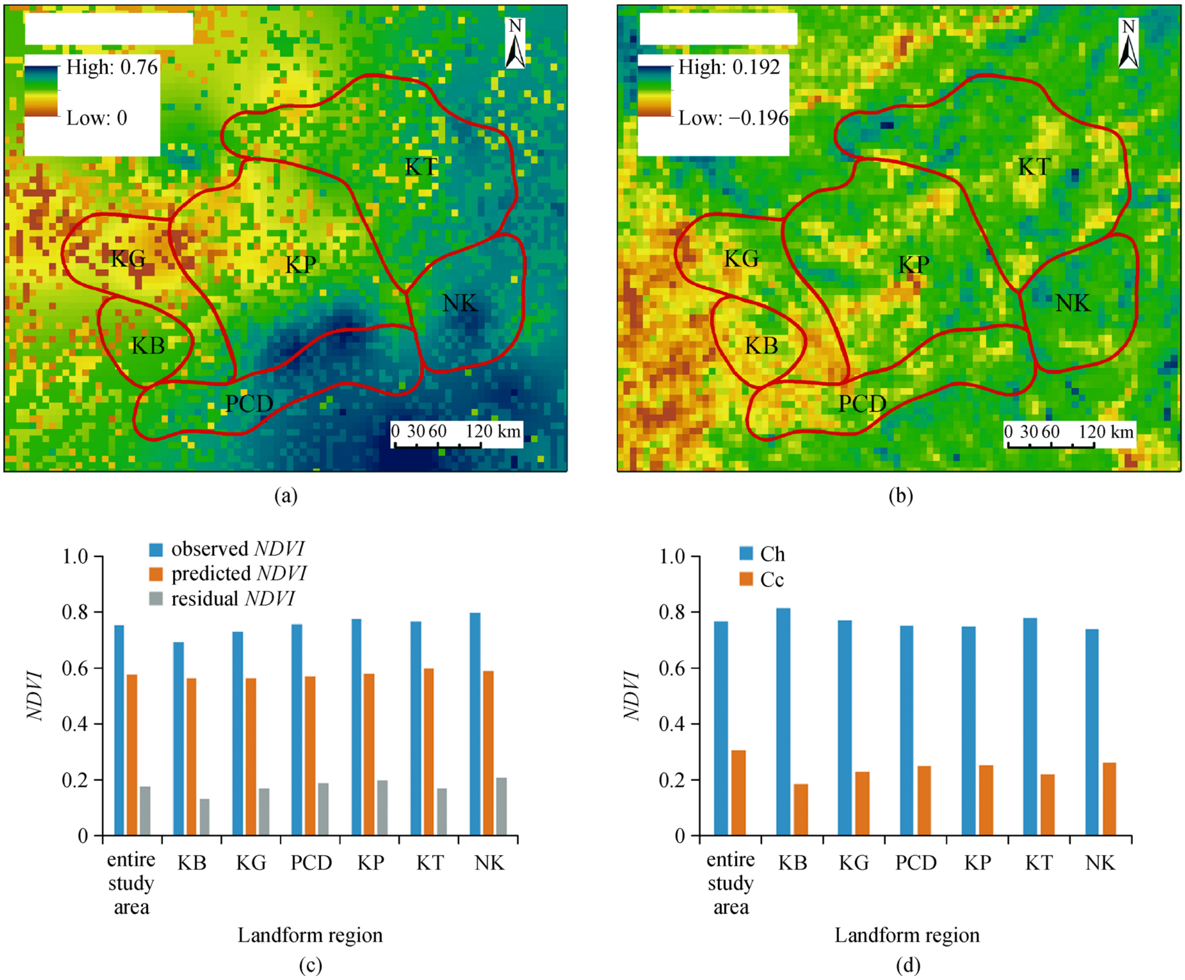


Fig. 13 Spatial distribution of (a) predicted *NDVI* and (b) residual *NDVI*; average observed, predicted, and (c) residual *NDVI*; and contribution of human activities and climatic factors to vegetation dynamics (d) for entire study area and each landform region in Guizhou Province during 2002–2015. (Ch—contribution of human activities; Cc—contribution of climatic factors; Cvd—contribution to vegetation dynamics; KB—Karst Basin; KG—Karst Gorge; KP—Karst Plateau; KT—Karst Trough Valley; NDVI—Normalized-Difference Vegetation Index; NK—Non-Karst Area; PCD—Peak Cluster Depression)

positively with temperature and negatively with precipitation in the study area (Table 1). Exceptions to the positive correlation with temperature were in Panxian, Anshun, and Guiyang, and exceptions to the negative correlation with precipitation were in some areas that are mainly in eastern and northern Guizhou Province (Fig. 12). Overall, when compared to precipitation, temperature was the dominant climatic factor influencing vegetation change. We account for this as follows.

Guizhou Province has extensive outcroppings of carbonate rock, covering ~73% of the total area. The carbonates (particularly limestone) are highly weathered and permeable (Jiang et al., 2014). The rate of soil formation is low, soil cover is scarce and soil layers thin, the surface is broken, and the water-holding capacity is extremely low in this region. Also, the lithology and hydrogeology are complex in the karst area, which is characterized by a typical dualistic 3-D hydrogeological structure (Wu et al., 2017). Even given the typical subtropical climate regime, with an annual precipitation of ~1200 mm, the large amount of rainfall rapidly passes through the well-develop surface-rock cracks, numerous fissures, and underground channels. Also, soil profiles in this area commonly are missing the C-horizon, which normally would keep the soil layer adhered to the bedrock. Furthermore, the huge topographic relief and steep slopes created by repetitive tectonic movement provide kinetic energy for overland flow. Heavy precipitation easily depletes the topsoil, nutrients, and organic materials, and such deficiencies restrict vegetation growth. In addition, owing to the effects of the subtropical climate and marked differences in altitude, the karst regions of southwestern China experience mainly cloudy weather, particularly in the mountainous areas. More precipitation generally increases the cloudy weather, decreasing solar penetration and thereby restricting photosynthesis and vegetation growth. Thus, high precipitation's ultimately inhibiting vegetation growth can explain why precipitation and vegetation cover are negatively correlated in this area. The exceptions in the eastern and northern parts of the province are interpreted as due to the thick soil layers' strong water-holding capacity, which supports vegetation growth and thus the positive correlation with precipitation.

Huang et al. (1988) discussed the factors of climate and weather, topography, and reduced solar radiation in large parts of the province, which we incorporated into the above explanation of some exceptions involving precipitation. Regarding temperature, its increase is usually accompanied by sunny days, with the corresponding increase in solar radiation penetrating to the land surface, which in turn results in the vegetation's increased photosynthesis. Consequently, increased temperature normally results in a positive correlation with vegetation growth. However, although the temperature generally was positively correlated with vegetation cover across most of the study area, the correlation was not very obvious in Panxian, Anshun, and Guiyang. The reason may be that in recent years Panxian, Anshun, and Guiyang have undergone dramatic land-use/land-cover changes, accelerating urbanization; such changes may have obscured the correlation between vegetation changes and apparently natural causes (such as temperature), instead being overpowered by the effects of human activities. For much of the karst areas, where the land was affected by human activities, although notable vegetation recovery has occurred (such as by vegetation-restoration measures), vegetation degradation is also evident locally — in areas of accelerated urbanization and agricultural development. So, this local-degradation issue should not be ignored in order to prevent karst rocky desertification and instead support sustainable development in karst areas.

The *NDVI* generally showed positive correlation with monthly temperature in summer, which is the growing season. Because increased temperature can improve light-use efficiency, temperature is a key factor driving vegetation growth and hence *NDVI* increase. However, the *NDVI* also showed obvious positive correlation with monthly temperature in winter and spring, which may have occurred as a result of recent dramatic urbanization, causing increased combustion of fossil fuels, which in turn would have increased the heat and carbon dioxide in winter, thus elevating air temperature. Due to the increased temperature, many species are no longer dormant in winter. Consequently, it finally led to an earlier initiation of the growing season and more-robust vegetation growth. Also, increased vegetation cover manifested mainly as increased leaf area index caused by the additional vegetation growth largely attributed to abundant precipitation and high temperatures in spring.

The results of our study indicate that the contribution of human activities to vegetation change was 76%, while that of climatic factors was 24%, and these are the same percentages that were obtained by Zhang et al. (2019). In summary, when compared to natural causes such as climatic factors and geographic characteristics, human activities were the main driving force affecting the vegetation dynamics in Guizhou Province. From our present study, we conclude that the reason for the larger influence of human activities than that of climatic variables on vegetation dynamics in Guizhou Province could be that the subtropical humid monsoon climate, which provides abundant water and heat, would require significant climate change to effect obvious changes in vegetation condition. Accordingly, the contribution of climatic factors to vegetation dynamics was relatively low. In contrast, against the backdrop of a typical and fragile karst ecosystem, intense human activities — such as slope cultivation and forest exploitation — easily lead to obvious vegetation degradation. Also, given the abundant water and heat resources, even without implementation of vegetation-restoration projects (such as the Green for Grain Project), vegetation cover can experience obvious improvement under decreasing human disturbance. For example, after a few years of abandonment, vegetation will recover by natural restoration of formerly cultivated land.

4.2 Spatial heterogeneity of vegetation dynamics and its driving factors

Our study results demonstrate that the vegetation dynamics and its response to climatic variables exhibited obvious spatial heterogeneity in Guizhou Province. High vegetation characterized most of the study area, low vegetation was sparsely distributed in the center and western margin of the study area, and vegetation cover was generally higher in the non-karst areas than in the karst areas. Also, vegetation cover was positively correlated with climatic variables throughout the non-karst areas. The reasons may be that the non-karst areas are greatly affected by the tropical monsoon climate, which generates abundant precipitation and elevated temperatures (mainly in summer), and commonly are characterized by a thick soil layer and low altitude, both of which are conducive to vegetation growth. Thus, against the background of advantageous natural resources, the increased temperature and precipitation jointly caused the increase in vegetation cover.

In contrast, low vegetation cover was mainly observed in the karst areas (Karst Plateau, Peak Cluster Depression, Karst Basin, Karst Trough Valley, and Karst Gorge). The reasons might be that in such a fragile, typical karst ecological and geological environment, Guizhou karst mountains inspire a high degree ecosystem sensibility and vulnerability, stemming from the high degree of landscape heterogeneity, extremely low rate of soil formation, various topographic features, low environmental capacity, weak resisting disturbing capability, and poor stability. Coupled with strongly disturbing monsoon activity, population pressures, and high-intensity human disturbance, these jointly caused the low vegetation cover in the karst areas. Although vegetation cover generally showed an improving trend under the implementation of a series of vegetation-restoration projects in most of the karst areas, at the same time dramatic land-use/land-cover change and urban expansion have resulted in vegetation degradation in some regions. Examples are found in the Karst Gorge and Karst Plateau, where the extremely thin soil layer, lack of surface-water sources, and population pressures are far beyond the carrying capacity of the fragile karst ecosystem; these areas eventually had reduced vegetation cover. Also, we found vegetation dynamics in these areas was not very sensitive to climatic factors; it was mainly influenced by human activities. The results of this study indicate that human activities are the dominant factors affecting vegetation dynamics in the typical karst areas of Guizhou Province.

4.3 Applicability and limitations of present study

Most previous related studies have reported mainly that the vegetation cover has been generally improved in recent decades in Guizhou Province (Dan and Xie, 2009; Zheng et al., 2009; Ma et al., 2016; Wang et al., 2016; Tian et al., 2017; Zhang et al., 2019; Xu and Chen, 2019). Also, they have reported that temperature rather than precipitation was the dominant climatic factor that influences vegetation changes. The results obtained in those previous studies agree well with our present study based on the GIMMS *NDVI* data set, which covers a longer period of time, including more-recent years. It helped to confirm that the vegetation cover has greatly improved and has developed a tendency toward sustainability and has encouraged the idea that the increasing trend will continue. Meanwhile, our results also indicated remarkable results from several ERPs, which were put forward by national and local government entities in the karst areas. Too, compared to many previous studies, our work not only assessed the vegetation dynamics and its response to influential factors at annual and seasonal scales over the entire study area and across different landforms, but also our work separated the contributions of climatic variables and human activities to vegetation changes. Generally speaking, the results of our research greatly enrich our knowledge of vegetation dynamics and its driving factors, and provide a scientific basis for vegetation-restoration practices, and improve environmental management in karst areas.

However, there were some limitations of the present study. For instance, the GIMMS *NDVI* data set was applied to indicate the status of vegetation growth in Guizhou Province, but there are many pixels that record mixed reflectance — from vegetation, rock outcrop, soil types, and other land cover — at the 8 × 8-km resolution of the satellite data. However, compared with the Pathfinder AVHRR land data set and the SPOT *NDVI* and MODIS *NDVI* data set, the GIMMS *NDVI* data set covers a relatively longer period and can better render interannual and interdecadal variability. Too, when the GIMMS *NDVI* data set was generated, the effects of calibration, geometry, viewing angle and volcanic aerosols were reduced or eliminated. It also is one of the most important and widely used data set for large-scale vegetation studies, not only because of its relative continuity in spatiotemporal terms, but also its high correlation with some key vegetation parameters — such as net primary production, leaf area index, and the fraction of photosynthetically active radiation absorbed by the vegetation canopy (Liu et al., 2011). Therefore, we used the GIMMS *NDVI* data set to evaluate the vegetation dynamics in the present work. However, in future research, the downscaling method should be used to convert the *NDVI* data set to a higher spatial resolution, which can be helpful for evaluating the vegetation dynamics more accurately in the karst areas.

Natural causes and human disturbances separately or jointly affect vegetation dynamics on global and regional scales. Conversely, vegetation changes strongly influence the natural environment (such as climate systems) by modifying the albedo, aerodynamic roughness, and land-surface evapotranspiration. In our present study and others' related research, vegetation cover was found to have experienced an obviously increasing trend during 1982–2015. With the recent implementation of such ERPs as the Green for Grain and the Karst Rocky Desertification Comprehensive Control and Restoration projects, vegetation cover is experiencing a tendency for continuous improvement. Particularly with the implementation of the anti-poverty project, there will be more farmland abandoned with the large migration from rural to urban communities, and, with more dramatic human disturbances such as increased urbanization. Spatial heterogeneity between rural and urban areas will become even more obvious. This would increase the heterogeneity of the surface landscape and accelerate the cross-ventilation, resulting in more complexity of the relationship between vegetation and its driving factors.

Vegetation dynamics is also affected by natural disturbances such as fire and insect outbreaks, which can shift forests back to a young age structure. The expression of vegetation cover by the *NDVI* also may be affected by topographic characteristics, soil and vegetation types, the resolution of remote-sensing data, and the accuracy of the interpolation method used (Liu et al., 2011). Beyond temperature and precipitation, climatic factors such as relative humidity, solar radiation, and wind speed also have an influence on vegetation dynamics, but their effects have not been analyzed in the present work. Therefore, further study of the Guizhou Province is required to obtain additional data on these topics, and further methodological efforts will enable more-precise findings to emerge.

Finally, in this study, correlation analysis showed that the temperature (in January, February, and June) and the precipitation (in February and June) were obviously related to *NDVI* during 1982–2001, and the correlation generally exceeded the 0.05 significance level. Although we developed the regression model for the *NDVI* and those climatic factors for those five months by pixel-level calculations for each land-use/land-cover type, the correlation coefficient was not very high (~0.45). Also, in the study conducted in Guizhou Province by Zhang et al. (2019), the average correlation coefficient obtained from the *NDVI*–climate regression model (0.52) was similar to our results. The reasons that the correlation coefficient was only 0.5 might be the following: Because of the high degree of spatial heterogeneity in the karst mountains of Guizhou Province, the impacts of slope, aspect, and shadow could have further complicated land-surface spectral reflectance. Also, being available at only a coarse resolution (8 × 8 km), the same land-use types could have different spectral responses. Likewise, different land-use types could have similar spectral responses. All these reasons together make it challenging to develop a high-precision *NDVI*–climate regression model, for which the average error might be quite high. In summary, although there are some shortcomings in our *NDVI*–climate regression model, the results of our study can explain the variation characteristics of vegetation cover in the study area. We hope that this study can provide some useful direction for future research on vegetation dynamics in karst regions.

5 Conclusions

Based on long-term series of GIMMS *NDVI* and meteorological data sets, we evaluated the vegetation dynamics and its response to temperature, precipitation, and human activities in Guizhou Province during 1982–2015, with the following results:

1) The mean annual *NDVI* exhibited a significant increasing trend, with the variation rate of 0.01/10a during 1982–2015. Compared to the period 1982–2001, the *NDVI* showed a more obviously increasing trend for the period of 2002–2015. Also, the vegetation cover showed high spatial heterogeneity: High vegetation cover was found mainly in the center and western margin of the province, other parts of the study area had mainly low vegetation cover, and the vegetation cover was higher in non-karst areas than in karst areas. The monthly *NDVI* was highest in summer, more moderate in spring and autumn, and lowest in winter; this pattern was consistent with monthly temperature and precipitation. Overall, *NDVI* showed a marked similarity corresponding to the spatiotemporal-variation characteristics of climate.

2) The climate was found to be growing warmer and drier during 1982–2015. Correlation coefficients between *NDVI* and climatic variables varied geographically; they gradually decreased from east to west. High vegetation cover, found mainly in the Non-Karst Area and Karst Through Valley, was strongly correlated with climatic variables. In contrast, relatively low vegetation cover but an increasing trend characterized the Karst Plateau, Peak Cluster Depression, Karst Gorge, and Karst Basin. In general, vegetation cover correlated positively with temperature and negatively with precipitation. Across most of the study area, as a climate factor in vegetation change, temperature was more dominant than precipitation, particularly given that increased temperature could accelerate vegetation growth.

3) Large-scale ERPs have obviously improved vegetation cover in the study area in recent years. The contribution of human activities to vegetation changes was 76%, while the contribution of climatic factors was 24%. In summary, compared to natural forces such as climatic factors and geographic parameters, human activities were the main driving force affecting the vegetation dynamics. Positive human activities, in particular, have had obvious influence on vegetation dynamics. The results of this study can not only be helpful for understanding the relationship between vegetation dynamics and its driving factors in Guizhou Province, but are also proposed to be of high relevance for evaluating the effectiveness of ERPs and for providing a scientific basis for further vegetation-restoration practice in karst areas.

Acknowledgements This work was supported by the National Natural Science Foundation of China (Grant Nos. 41761003 and U1812401); the Guizhou Provincial Science and Technology Foundation (No. Qiankehe Jichu [2019]1433); the Project for National Top Discipline Construction of Guizhou Province: Geography in Guizhou Normal University (No. 85-01 2017 Qianjiao Keyan Fa); the Project of Innovation Program for Postgraduate Education of Guizhou Province: Xiong Kangning's studio of postgraduate supervisors for the karst environment of Guizhou Province (04 2016 Qianjiao Yanhe GZS Zi)

References

Beerling D, Woodward F, Lomas M, Jenkins A (1997). Testing the responses of a dynamic global vegetation model to environmental change: a comparison of observations and predictions. Glob Ecol Biogeogr Lett, 6(6): 439–450

Brandt M, Yue Y, Wigneron J P, Tong X, Tian F, Jepsen M R, Xiao X, Verger A, Mialon A, Al-Yaari A, Wang K, Fensholt R (2018). Satellite-observed major greening and biomass increase in south China Karst during recent decade. Earth's Future, 6(7): 1017–1028

Cai H, Yang X, Wang K, Xiao L (2014). Is forest restoration in the southwest China Karst promoted mainly by climate change or human-induced factors? Remote Sens, 6(10): 9895–9910

Cao L, Xu J, Chen Y, Li W, Yang Y, Hong Y, Li Z (2013). Understanding the dynamic coupling between vegetation cover and climatic factors in a semiarid region—a case study of Inner Mongolia, China. Ecohydrology, 6(6): 917–926

Chen C, Park T, Wang X, Piao S, Xu B, Chaturvedi R K, Fuchs R, Brovkin V, Ciais P, Fensholt R, Tømmervik H, Bala G, Zhu Z, Nemani R R, Myneni R B (2019). China and India lead in greening of the world through land-use management. Nat Sustain, 2(2): 122–129

Dan L, Xie M (2009). The spatio-temporal variation of leaf area index in Guizhou and its response to climate based on MODIS data. Climatic and Environmental Research, 14(05): 455–464 (in Chinese)

Davenport M, Nicholson S (1993). On the relation between rainfall and the Normalized Difference Vegetation Index for diverse vegetation types in East Africa. Int J Remote Sens, 14(12): 2369–2389

Evans J, Geerken R (2004). Discrimination between climate and human-induced dryland degradation. J Arid Environ, 57(4): 535–554

Gao J, Li S, Zhao Z, Cai Y (2012). Investigating spatial variation in the relationships between *NDVI* and environmental factors at multi-scales: a case study of Guizhou Karst Plateau, China. Int J Remote Sens, 33(7): 2112–2129

Hill M, Donald G (2003). Estimating spatio-temporal patterns of agricultural productivity in fragmented landscapes using AVHRR *NDVI* time series. Remote Sens Environ, 84(3): 367–384

Hu M, Mao F, Sun H, Hou Y (2011). Study of normalized difference vegetation index variation and its correlation with climate factors in the Three-River-Source region. Int J Appl Earth Obs Geoinf, 13(1): 24–33

Huang W, Tu Y, Yang L (1988) Vegetation of Guizhou. Guiyang: Guizhou People’s Publishing House

Ichii K, Kawabata A, Yamaguchi Y (2002). Global correlation analysis for NDVI and climatic variables and *NDVI* trends: 1982–1990. Int J Remote Sens, 23(18): 3873–3878

Ji L, Peters A (2003). Assessing vegetation response to drought in the northern Great Plains using vegetation and drought indices. Remote Sens Environ, 87(1): 85–98

Jiang L, Guli Jiapaer, Bao A, Guo H, Ndayisaba F (2017). Vegetation dynamics and responses to climate change and human activities in Central Asia. Sci Total Environ, 599–600: 967–980

Jiang Z, Lian Y, Qin X (2014). Rocky desertification in southwest China: Impacts, causes, and restoration. Earth Sci Rev, 132: 1–12 (in Chinese)

Liu W, Cai T, Ju C, Fu G, Yao Y, Cui X (2011). Assessing vegetation dynamics and their relationships with climatic variability in Heilongjiang province, northeast China. Environ Earth Sci, 64(8): 2013–2024

Liao Y, Yang F, Luo Y, Zhao T, Shang Y, Zhang X (2019). Regional climatology of aerosol distribution over the Yunnan Guizhou Plateau. Ecology and Environmental Science, 28(2): 316–323 (in Chinese)

Ma W, Wang X, Zhou N, Jiao L (2017). Relative importance of climate factors and human activities in impacting vegetation dynamics during 2000–2015 in the Otindag Sandy Land, northern China. J Arid Land, 9(4): 558–568

Ma S, An Y, Yang G, Zhang Y (2016). The analysis of the difference vegetation variation and driver factors on *NDVI* change in Karst region: a case on Guizhou. Ecology and Environmental Sciences, 25 (7): 1106–1114 (in Chinese)

Martínez B, Gilabert M A (2009). Vegetation dynamics from NDVI time series analysis using the wavelet transform. Remote Sens Environ, 113(9): 1823–1842

Mata González R, Martin D W, McLendon T, Trlica M J, Pearce R A (2012). Invasive plants and plant diversity as affected by groundwater depth and microtopography in the Great Basin. Ecohydrology, 5(5): 648–655

Meng J, Wang J (2007). Responses of vegetation changes in southwest karst area to climate change since the 1980s. Geogr Res, 5: 857–865 (in Chinese)

Ni J (2011). Impacts of climate change on Chinese ecosystems: key vulnerable regions and potential thresholds. Reg Environ Change, 11 (S1): 49–64

Piao S, Mohammat A, Fang J, Cai Q, Feng J (2006). NDVI-based increase in growth of temperate grasslands and its responses to climate changes in China. Glob Environ Change, 16(4): 340–348

Pouliot D, Latifovic R, Olthof I (2009). Trends in vegetation *NDVI* from 1 km AVHRR data over Canada for the period 1985–2006. Int J Remote Sens, 30(1): 149–168

Song Y, Ma M (2011). A statistical analysis of the relationship between climatic factors and the Normalized Difference Vegetation Index in China. Int J Remote Sens, 32(14): 3947–3965

Theurillat J, Guisan A (2001). Potential impact of climate change on vegetation in the European Alps: a review. Clim Change, 50(1–2): 77–109

Tong X, Wang K, Brandt M, Yue Y, Liao C, Fensholt R (2016). Assessing future vegetation trends and restoration prospects in the Karst regions of southwest China. Remote Sens, 8(5): 357

Tong X, Wang K, Yue Y, Brandt M, Liu B, Zhang C, Liao C, Fensholt R (2017). Quantifying the effectiveness of ecological restoration projects on long-term vegetation dynamics in the Karst regions of southwest China. Int J Appl Earth Obs Geoinf, 54: 105–113

Tong X, Brandt M, Yue Y, Horion S, Wang K, Keersmaecker W D, Tian F, Schurgers G, Xiao X, Luo Y, Chen C, Myneni R, Shi Z, Chen H, Fensholt R (2018). Increased vegetation growth and carbon stock in China karst via ecological engineering. Nature Sustainability, 1(1): 44–50

Tourre Y, Jarlan L, Lacaux J, Rotela C, Lafaye M (2008). Spatio-temporal variability of *NDVI*–precipitation over southernmost South America: possible linkages between climate signals and epidemics. Environ Res Lett, 3(4): 044008

Tian P, Xu D, Ding L, Chen J (2017). Analysis of spatial-temporal variation characteristic of vegetation in Guizhou during 2005–2014 period based on MODIS-*NDVI*. Journal of Guizhou Meteorology, 41 (2): 8–13

Wang S (2002). Concept deduction and its connotation of karst rocky desertification. Carsologica Sinica, 21(2): 101–105 (in Chinese)

Wang S, Li Y, Li R (2003). Karst rocky desertification: formation background, evolution and comprehensive taming. Auaternary Sciences, 23(6): 657–666 (in Chinese)

Wang S, Liu Q, Zhang D (2004). Karst rocky desertification in southwestern China: geomorphology, landuse, impact and rehabilitation. Land Degrad Dev, 15(2): 115–121

Wang B, Yang S (2006). Study on change of vegetation cover in Guizhou Karst region based on NOAA/AVHRR. Carsologica Sinica, 25(2): 157–162 (in Chinese)

Wang Y, Shen Y, Chen Y, Guo Y (2013). Vegetation dynamics and their response to hydroclimatic factors in the Tarim River Basin, China. Ecohydrology, 6(6): 927–936

Wang Z, Wang Q, Li S, Wang P, Liu X, Xie C, Shi J, Wu G, Wang X, Lu R, Mo B (2016). The growth characteristics of vegetation in the Karst regions of Guizhou from1982 to 2012. Pratacult Sci, 33(11): 2180–2188 (in Chinese)

Wei Y, Yu L, Zhang J, Yu Y, Deangelis D L (2011). Relationship between vegetation restoration and soil microbial characteristics in degraded Karst regions: a case study. Pedosphere, 21(1): 132–138

Wu L, Wang S, Bai X, Luo W, Tian Y, Zeng C, Luo G, He S (2017). Quantitative assessment of the impacts of climate change and human activities on runoff change in a typical Karst watershed, SW China. Sci Total Environ, 601–602: 1449–1465

Xiong K, Li J, Long M (2012). Features of soil and water loss and key issues in demonstration areas for combating Karst rocky desertification. Acta Geogr Sin, 67(7): 878–888 (in Chinese)

Xu Y F, Chen F H (2019). FU liang-tong analysis on vegetation coverage change and its spatio-temporal pattern in Guizhou Plateau during recent 15 years. Journal of West China Forestry Science, 48 (1): 1–6 (in Chinese)

Yuan, D. (2014) The Research and Countermeasures of Major Environmental Geological Problems in Karst Areas of Southwest China. Beijing: Science Press

Zhang C, Qi X, Wang K, Zhang M, Yue Y (2017). The application of geospatial techniques in monitoring Karst vegetation recovery in southwest China: a review. Prog Phys Geogr, 41(4): 450–477

Zhang G, Xu X, Zhou C, Zhang H, Ouyang H (2011). Responses of grassland vegetation to climatic variations on different temporal scales in Hulun Buir grassland in the past 30 years. J Geogr Sci, 21 (4): 634–650

Zhang J, Zhou X, Jiang X, Yang J, Niu Q (2019). Analysis of vegetation variation and its influencing factors in Guizhou plateau under the background of ecological engineering construction. Resources and Environment in the Yangtze Basin, 28(7): 1623–1633 (in Chinese)

Zheng Y, Liu H, Wu R, Wu Z, Niu L (2009). The *NDVI* variation in Guizhou Province and its correlation with main climate factors. Journal of Ecology and Rural Environment, 14(05): 455–464 (in Chinese)

Zhong L, Ma Y, Salama M, Su Z (2010). Assessment of vegetation dynamics and their response to variations in precipitation and temperature in the Tibetan Plateau. Clim Change, 103(3–4): 519–535

Zhou Q, Luo Y, Zhou X, Cai M, Zhao C (2018). Response of vegetation to water balance conditions at different time scales across the Karst area of southwestern China—a remote sensing approach. Sci Total Environ, 645: 460–470