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Spatial-temporal Changes of Vegetation Cover in Guizhou Province, Southern China

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Abstract: Guizhou Province is an important karst area in the world and a fragile ecological area in China. Ecological risk assessment is very necessary to be conducted in this region. This study investigates different characteristics of the spatial-temporal changes of vegetation cover in Guizhou Province of Southern China using the data set of SPOT VEGETATION (1999–2015) at spatial resolution of 1-km and temporal resolution of 10-day. The coefficient of variation, the Theil-Sen median trend analysis, and the Mann-Kendall test are used to investigate the spatial-temporal change of vegetation cover and its future trend. Results show that: 1) the spatial distribution pattern of vegetation cover in Guizhou Plateau is high in the east whereas low in the west. The average annual normalized difference vegetation index (NDVI) from west to east is higher than that from south to north. 2) Average annual NDVI improved obviously in the past 17 years. The growth rate of average annual NDVI is 0.028/10 yr, which is slower than that of vegetation in the country (0.048/10 yr) from 1998 to 2007. Average annual NDVI in karst area is lower than that in non-karst area. However, the growing rate of average annual NDVI in karst area (0.030/10 yr) is faster than that in non-karst area (0.023/10 yr), indicating that vegetation coverage increases more rapidly in karst area. 3) Vegetation coverage in the study area is stable overall, but fluctuates in the local scales. 4) Vegetation coverage presents a continuous increasing trend. The Hurst exponent of NDVI in different vegetation types has an obvious threshold in various elevations. 5) The proportion of vegetation cover with sustainable increase is higher than that of vegetation cover with sustainable decrease. The improvement in vegetation cover may expand to most parts of the study area.

Keywords: vegetation cover; spatial-temporal change; trends analysis; normalized difference vegetation index (NDVI); Hurst exponent; Guizhou Province, China

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1 Introduction

Dynamic monitoring of vegetation and its variations is an important concern in ecological environment studies (Berlin *et al.*, 2000). This subject is related to changes in the ecological environment and the sustainable development of humans (Schweers *et al.*, 2011) and has received considerable attentions in the field of ecology (Tucker *et al.*, 1986; Lioubimtseva *et al.*, 2005; Fensholt *et al.*, 2009; Jugder *et al.*, 2011; Miao *et al.*, 2014).

The linear regression method has been widely used for analyzing vegetation dynamic trends, such as long

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time series analysis of vegetation cover changes (Zhang *et al.*, 2011; Liang *et al.*, 2013; Mohammat *et al.*, 2013). Although criticized for its inability to reflect non-linear characteristics in the process of vegetation dynamics (Li *et al.*, 2008) as well as the smoothened mutation in the regression process, the method is still widely used in large-scale vegetation dynamic studies because of its simplicity and robustness (Fensholt *et al.*, 2009). However, non-linear variations exist when considering vegetation changes induced by drought. Mohammat *et al.* (2013) chose three time periods (1982–2009, 1990–2009, and 2000–2009) to study seasonal vegetation trends using data from Global Inventory Modeling and Mapping Studies (GIMMS). Zhang *et al.* (2010) also used GIMMS data from 1982 to 2007 to study the vegetation dynamic trends in the southwestern North America. Using non-linear methods to study vegetation in different stages can efficiently explain the vegetation growth and its responses to meteorological factors. For example, Park and Sohn (2010) used GIMMS data from 1982 to 2006 and employed the empirical orthogonal function to study vegetation cover in East Asia. Similarly, De Jong *et al.* (2013) used the method called breaks for additive season and trend to extract the rheology and mutation of vegetation based on GIMMS data. Xue *et al.* (2013) used integrated fuzzy logic with a piecewise linear regression method to study the vegetation change in the American Yukon and the Alaskan basin; their results showed that the non-linear change in vegetation is the main cause of fire disturbance. Jeong *et al.* (2011) applied the maximum covariance analysis method to study vegetation change based on GIMMS data and found that vegetation changes present a non-linear trend in the high latitudes of the Northern Hemisphere. Piao *et al.* (2011) used piecewise linear regression methods to study non-linear response vegetation in Eurasia for meteorological factors based on GIMMS data (1982–2006); their comparison and analysis show that the non-linear method is better than the linear regression method. Zhang *et al.* (2013) studied the vegetation cover in the Kosi River of the Himalayan mountain range, showing that vegetation has obvious non-linear characteristics in the progress of vegetation growth.

Based on the previous findings and current researches mentioned above, the present research questions are as follows: what are the typical non-linear methods for studying the vegetation growth in different stages? What are the spatial-temporal patterns of vegetation dynamics in a region using a long-term remotely sensed vegetation data set? How can the vegetation trends in the future be quantitatively detected using mathematical models? The Theil-Sen median trend analysis (Fensholt and Proud, 2012; Huang *et al.*, 2012; Wu *et al.*, 2013) and the Mann-Kendall (MK) test (Qiu and Cao, 2011) are two popular non-linear methods. Using these methods, vegetation trends cannot be affected easily by outliers. Combining the two methods is robust in exploring significant trends in vegetation changes (Pouliot *et al.*, 2009; Fensholt *et al.*, 2012; Fuller and Wang, 2014). The vegetation trends refer to the prevalent directions of vegetation dynamics during the study period and the possible directions of vegetation dynamics after the study period. The latter directions are significantly important because they can reflect the vegetation change in future. The Hurst exponent has been used to quantitatively detect the sustainability of vegetation time series.

Guizhou Province in Southern China is one of the most concentrated and most typical karst areas in the world. The region is located in the Yangtze River and Pearl River watershed area, and its ecological location requires regional ecological risk assessment. However, research on the change in vegetation cover over a long time series in the Guizhou Province is limited, and the methodology used is confined to linear regression and correlation analysis methods (Meng and Wang, 2007; Zhang *et al.*, 2011). These methods assume that errors are homoscedastic and serially uncorrelated, and lack effective measurements for time series data due to the assumed presence of systematic errors. Past research in Guizhou Province is based mainly on the relationship between 8-km GIMMS normalized difference vegetation index (NDVI) data and climate factors. The low spatial resolution of remote sensing data weakens somehow the spatial-temporal pattern of vegetation cover studied. Existing studies can reflect the spatial-temporal variation characteristics of vegetation cover in Guizhou Province, but they cannot fully reflect the characteristics of vegetation cover in the long-time series. The robust Theil-Sen median (TS) trend analysis and the Mann-Kendall (MK) test have been rarely used to study spatial-temporal pattern of vegetation cover and its current trend. The non-linear method of the Hurst exponent has also been scarcely used to quantitatively detect the sustainability of vegetation cover for future trends in the long time series.

In the present study, NDVI time series data from 1999 to 2015 are obtained based on the data set of SPOT VEGETATION (SPOT VGT) at a resolution of 1 km and temporal resolution of 10 days. The coefficient of variation, the Theil-Sen median trend analysis, and Mann-Kendall test are used to investigate the spatial-temporal changes of vegetation cover and its future trend. Studying the ecological changes of different geological backgrounds and evaluating the vegetation change trend from different spatial-temporal scales can provide scientific bases and technical support for the ecological restoration in Guizhou Province, China.

2 Materials and Methods

2.1 Study area

Guizhou Province is part of the eastern Yunnan-Guizhou Plateau, belonging to the national terrain of the second step. It is located in the Pearl River Basin and the Yangtze River Basin watershed areas (Figs. 1a and 1b) at the range of 24°37′N–29°13′N, 103°36′E–109°35′E, and with an area of 176 167.52 km^2. The elevation of Guizhou Province ranges from 229 to 2794 m. The climate is humid subtropical monsoon, with an annual mean temperature of 15.5℃ and mean annual precipitation of 1400 mm. Over 70% of the annual rainfall occurs from May to September, brought in by the East Asian and Indian Summer Monsoons. Carbonate rocks in karst area are widespread and account for 62% of total area of Guizhou Province (Wang *et al.*, 2004; Bai *et al.*, 2013). Considering geological, tectonic, and climatic effects, the karst area is affected by intensive human activities. Such area is sensitive to environmental changes and to the complexity and diversity of soil types. Given the special geographic location, the vegetation type in the area varies.

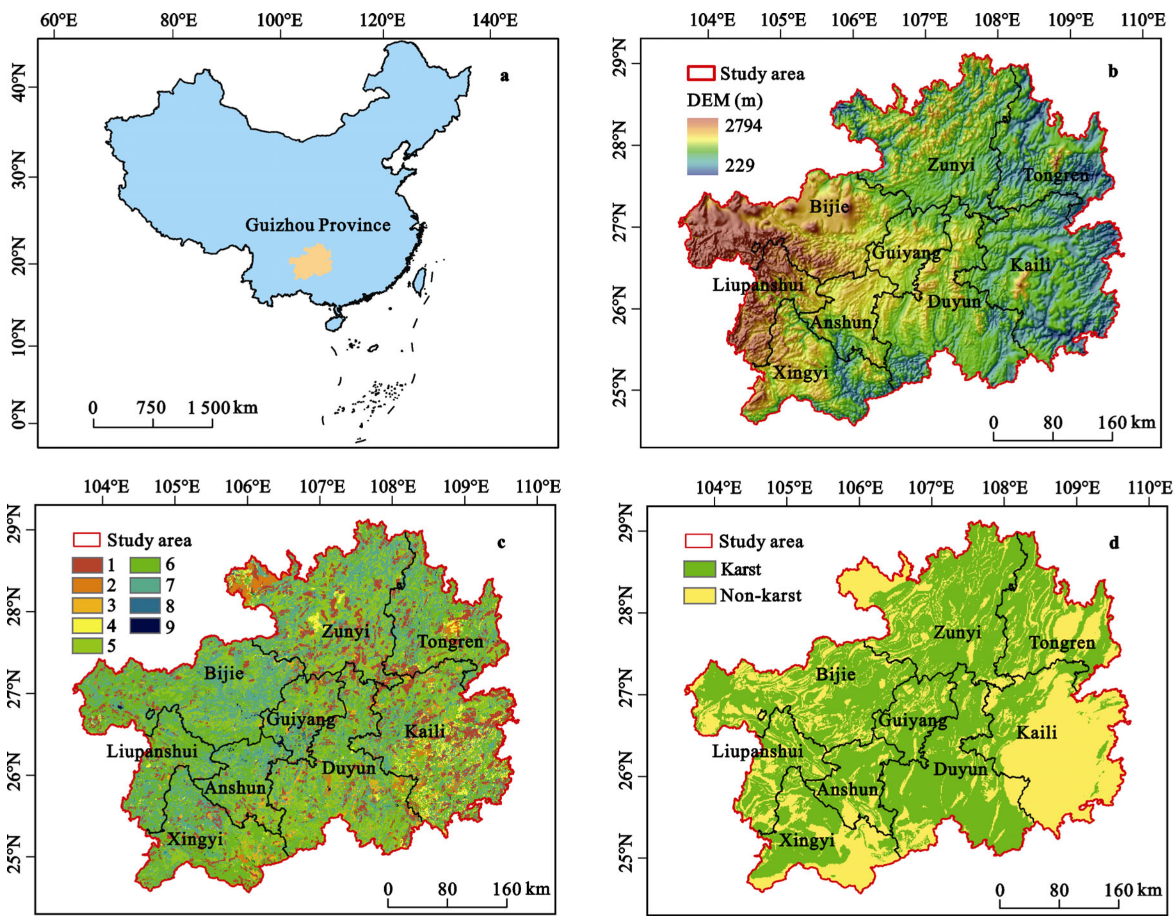

Fig. 1 Location in China (a), topography (b), vegetation types (c) and geological backgrounds (d) of the study area. DEM is Digital Elevation Model. 1: Evergreen needleleaf forest (ENF); 2: Evergreen broadleaf forest (EBF); 3: Deciduous broadleaf forest (DBF); 4: Mixed forest (MF); 5: Closed shrublands (CH); 6: Grasslands (GL); 7: Croplands (CL); 8: Urban and built-up lands (UBL); 9: Barren or sparsely vegetated lands (BSVL)

2.2 Data sources

This study uses the vegetation map of Guizhou Province (Fig. 1c), different geological background data (Fig. 1d), and the data set of SPOT VGT. The vegetation map at 1：100 000 scale is produced by the Institute of Botany CAS (http://www.ibcas.ac.cn/). The classification system consists 9 vegetation/land use categories (Fig. 1c): evergreen needleleaf forest (ENF), evergreen broadleaf forest (EBF), deciduous broadleaf forest (DBF), mixed forest (MF), closed shrublands (CH), grasslands (GL), croplands (CL), urban and built-up lands (UBL), and barren or sparsely vegetated lands (BSVL). Different geological background data are obtained from the State Key Laboratory of Environmental Geochemistry at the Institute of Geochemistry of Chinese Academy of Sciences. The data set of SPOT VGT from January 1999 to December 2015 at spatial resolution of 1-km and temporal resolution of 10-day is obtained from the free website (http://www.vgt.vito.be/). The monthly NDVI data are calculated by the maximum value composite method, which minimizes the effects of clouds, atmospheric conditions, and solar altitude (Holben, 1986). The annual NDVI data sets are the average of monthly NDVI data sets.

2.3 Methods

2.3.1 Coefficient of variation

The spatial fluctuation value of vegetation is used mainly to reflect the discrete degree of the NDVI data and the inter-annual or annual volatility of vegetation (Tucker *et al.*, 1991; Milich and Weiss, 2000). It can be measured using the coefficient of variation (CV).

2.3.2 Theil-Sen median trend analysis and Mann-Kendall test

This study combines the Theil-Sen median (TS) trend analysis and the Mann-Kendall (MK) test to analyze the time series of vegetation. Significant trends can explain the change in long-term NDVI. Theil-Sen median (TS) trend is calculated by

$$TS = \text{median}\frac{x_j - x_i}{j - i} \quad 1 < i < j < n \tag{1}$$

where x_i and x_j represent the NDVI values of years *i* and *j*, respectively. In case of $TS > 0$, the NDVI presents an increasing trend; otherwise, it shows a decreasing trend.

The MK trend test is a non-parametric statistical test method used to assess the significance of TS trend (Fuller and Wang, 2014). It has been widely applied to analyze the trends and variations in sites with hydrological and meteorological time series, and has also been used to study vegetation variations over long periods (Yue *et al.*, 2002). This non-parametric statistical test is advantageous because samples do not need to follow certain distributions and are free from the interference of outliers. For a time series $NDVI_t$, the statistic *Z* is defined as:

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{Var(S)}} & (\mathrm{S} > 0) \\ 0 & (S = 0) \\ \dfrac{S+1}{\sqrt{Var(S)}} & (S < 0) \end{cases} \tag{2}$$

where $S = \sum_{j=1}^{n-1}\sum_{i=j+1}^{n} \mathrm{sgn}(NDVI_j - NDVI_i)$

$$Var(s) = \frac{n(n-1)(2n+5)}{18}$$

$$\mathrm{sgn}(NDVI_j - NDVI_i) = \begin{cases} 1 & (NDVI_j - NDVI_i > 0) \\ 0 & (NDVI_j - NDVI_i = 0) \\ -1 & (NDVI_j - NDVI_i < 0) \end{cases} \tag{3}$$

where $NDVI_i$ and $NDVI_j$ represent the NDVI value at time *i* and *j*, *n* is the length of time series (17 years), and sgn is the *sgn* function. The value of *Z* ranges from $-\infty$ to $+\infty$. The normal distribution table indicates that, for a given significance level of 0.05, if $|Z| > 1.96$, then the time series has a significant variation at the level of 0.05.

2.3.3 Hurst exponent

The rescaled range (R/S) analysis, proposed by the British hydrologist Harold Edwin Hurst (1951), explores trends in the time scale to study natural and socio-economic phenomena of non-linear quantity and the prediction method. He found that a drought situation is not representative of the traditional hydrological statistics of the Nile River Basin, as envisaged, but is a random phenomenon. Persistent drought incidents result in continuous drought. Mandelbrot and Wallis (1969) improved this theory, which has been widely used in the fields of hydrology, climatology, economics, geology, and geochemistry. It has also been applied in detecting the time series of vegetation variations.

The basic principle of the R/S analysis is as follows.

Defined a time series ξ_t (t = 1, 2, ..., N), divide the time series into q subseries of ξ_t, and the mean sequence is defined as follows:

$$\overline{\xi}_q = \frac{1}{q}\sum_{t=1}^{q}\xi_t \tag{4}$$

(1) To calculate the accumulated deviation,

$$X_{(t,q)} = \sum_{t=1}^{q}(\xi_t - \overline{\xi}_q) \tag{5}$$

(2) To build the range sequence,

$$R_q = \max X_{(t,q)} - \min X_{(t,q)} \tag{6}$$

(3) To build the standard deviation sequence,

$$S_q = \left[\frac{1}{q}\sum_{t=1}^{q}(\xi_t - \overline{\xi}_q)^2\right]^{\frac{1}{2}} \tag{7}$$

(4) Introducing the dimensionless ratio into rescale, obtains

$$\frac{R_q}{S_q} = \frac{\max X_{(t,q)} - \min X_{(t,q)}}{\left[\frac{1}{q}\sum_{t=1}^{q}(\xi_t - \overline{\xi}_q)^2\right]^{\frac{1}{2}}} \tag{8}$$

where q = 1, 2, …, N and $1 \le t \le q$. Ratio $R_q/S_q \propto q^H$, then a Hurst phenomenon exists in the NDVI time series of vegetation. H is the Hurst exponent. The Hurst exponent can be expanded from 0 to 1 and in three types. First, when $H = 0.5$, the NDVI time series is a stochastic series without sustainability. Second, when $H > 0.5$, the sustainability of the NDVI time series exhibits the same trend as the NDVI time series in the future. Third, when $H < 0.5$, the anti-sustainability of the NDVI time series occurs.

The results of the Theil-Sen median trend analysis and the Hurst exponent are examined. An increasing or decreasing trend is obtained in the study area, and this trend is coupled with the sustainability analysis results. The results are divided into nine categories: strong sustainability and significant decrease, weak sustainability and significant decrease, strong sustainability and insignificant decrease, weak sustainability and insignificant decrease, weak sustainability and insignificant increase, strong sustainability and insignificant increase, weak sustainability and significant increase, strong sustainability and significant increase, and undetermined future variation in trends.

3 Results

3.1 Spatial distribution characteristics of vegetation cover

Given the topography and common meteorological factors that influence the spatial pattern of vegetation coverage in Guizhou Province, average annual NDVI exhibits an obvious regional differentiation. The spatial distribution map (Fig. 2a) shows that average annual vegetation coverage in Guizhou Province from 1999 to 2015 is 0.5742. It is high in the east whereas low in the west. This pattern is mainly attributed to the karst landform in the west of the study area. In this area, much of karst topography in the mid-west is partitioned, bedrock is exposed, and land degradation and desertification degrees are intense. As a result, the area exhibits low degree of vegetation cover. Statistical analysis of the different levels of average annual vegetation coverage shows that the area with a NDVI value under 0.2 accounts for only 0.0040%. This area is distributed mainly in the center of Guiyang, Zunyi, and Kaili, which is affected mainly by the nature of the underlying surface of the city. The surface density of the constructed land leads to an NDVI with a minimum value, i.e., 0.2 < NDVI < 0.3 accounting for 0.0466%. This area is distributed mainly in the downtown of Guiyang, Bijie and Kaili. This region is also affected by the underlying surface, thereby leading to low NDVI, i.e., 0.3 < NDVI < 0.4. This area accounts for 0.6729% and is distributed mainly in Guiyang, Anshun, the north of Liupanshui and the west of Bijie. This result is attributed to roads, residential areas, and rocky desertified areas that affect the vegetation cover. Accordingly, a low vegetation cover, i.e., 0.4 < NDVI < 0.5 is found, which accounts for 17.1361%. The area with 0.5 < NDVI < 0.6 is concentrated mainly in the western part of the research area, accounting for the largest proportion of 66.8249%. Given that the area with 0.6 < NDVI < 0.7 is distributed mainly in a typical non-karst area, highly concentrated in Kaili and the center of Tongren and accounting for 15.3048%. The area with a NDVI value greater than 0.7 only accounts for 0.0108% and is scattered in Tongren and Kaili Cities.

The variation of average annual vegetation coverage with longitude (Fig. 2b) and latitude (Fig. 2c) show that the average annual NDVI from west to east (0.5346) is higher than that from south to north (0.5314). The average annual NDVI increases from west to east (Fig. 2b) with a rate of 0.269/10°E (R^2 = 0.5679, P < 0.001). The curve of NDVI from 103.75°E to 104.25°E has a small peak. This finding is attributed to the area located in a non-karst region, which has relatively lush vegetation growth. A relatively low vegetation cover is observed between 106°E and 106.80°E in karst plateau due to the strongest influence of human activities. The value of NDVI between 108.80°E and 109.70°E is relatively high. This spatial pattern is relevant to special spatial distribution of non-karst landform. The mean NDVI from south to north (Fig. 2c) exhibits a slow upward trend, with a rate of 0.017/10°N. The overall spatial distribution of NDVI is 'two highs and one middle low'. 'Two highs' areas are distributed mainly in the north of non-karst area and the southern peak-cluster depression area. However, the value of NDVI in latitude from 26.30°N to 26.70°N decreases drastically because of the area with the underlying surface effect of the city (i.e., Guiyang City).

3.2 Temporal variation characteristics of vegetation cover

In the past 17 years, the NDVI of the study area has been progressively increasing (Fig. 3a). The linear tendency is 0.028/10 yr, which is slower than the growth of vegetation in Southwest China (0.054/10 yr) from 1998 to 2012 (Jing and Wang, 2014) and in the country (0.048/10 yr) from 1998 to 2007 (Qiu and Cao, 2011). The NDVI change during the study period is divided into five stages: three growth stages of periods 1999–2004, 2005–2009, and 2012–2015, and two declined phases of periods 2004–2005 and 2009–2012.

The average annual NDVI increases in un-synchronization from 1999 to 2015 under different geological backgrounds (Fig. 3b). The growth rate of average annual NDVI in different geological backgrounds is as follows: karst area (0.030/10 yr) > study area (0.028/10 yr) > non-karst area (0.023/10 yr). The fluctuation amplitude of average annual NDVI in non-karst area (0.5221 to 0.6043) is higher than that in karst area (0.4753 to 0.5580). However, the growth rate of average annual NDVI in karst area is nearly 1.3 times faster than that in non-karst area, indicating that vegetation cover grows more rapidly in the karst area. Overall, the amount and the fluctuation amplitude of NDVI under different geological backgrounds are inconsistent.

3.3 Stability of vegetation coverage change

The geometrical interval classification method (Xu, 2002) is used to divide the stability of the vegetation into five grades according to the results of the coefficient of variation analysis (Table 1). Areas with lower, low and moderate fluctuation account for 79.52% in the study area, whereas areas with high and higher fluctuation account for 20.48%. This finding indicates that the vegetation in the study area is stable overall, but fluctuates in local scales. Areas with high and higher fluctuation in karst area are larger than that in non-karst area. This difference is due to that the vegetation in karst area is more sensitive and discrete than that in non-karst area.

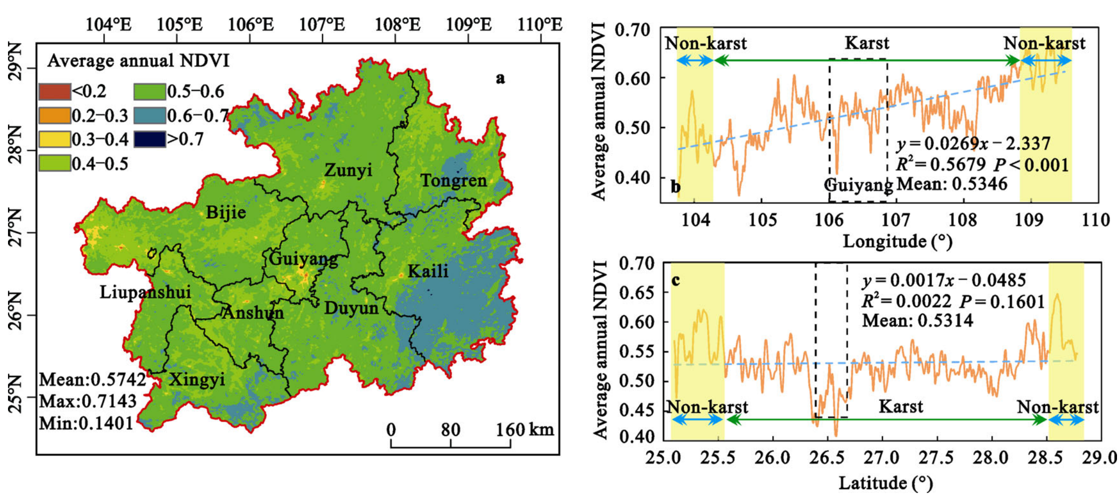

Fig. 2 Spatial distribution of average annual NDVI (a), NDVI trend of longitude (b) and latitude (c) from 1999 to 2015 in Guizhou Province of China

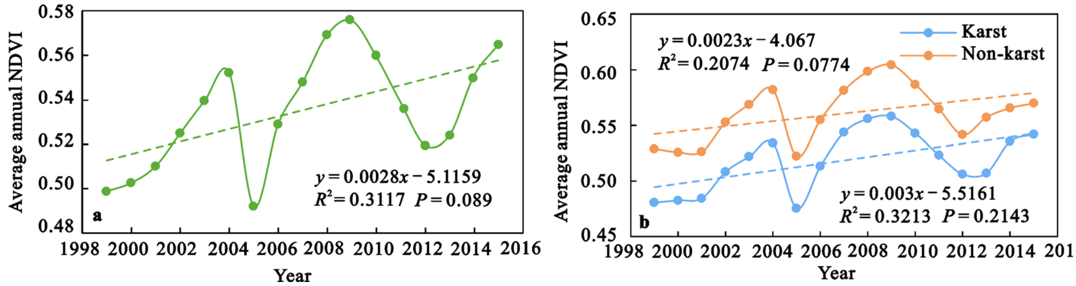

Fig. 3 Inter-annual variation of average annual NDVI (a) and growth rate of average annual NDVI in different geological backgrounds (b) from 1999 to 2015 in Guizhou Province of China

Table 1 Coefficient of variation (CV) of average annual NDVI in Guizhou Province of China from 1999 to 2015

Stability of average annual NDVI	CV_{NDVI}	Area percentage (%)		
		Study area	Karst area	Non-karst area
Lower fluctuation	(0.0400, 0.0860)	19.90	11.90	32.99
Low fluctuation	[0.0860, 0.1081)	31.29	31.59	30.82
Moderate fluctuation	[0.1081, 0.1286)	28.33	32.16	22.06
High fluctuation	[0.1286, 0.1558)	16.49	19.35	11.78
Higher fluctuation	[0.1558, 0.4756)	3.99	4.99	2.35

The spatial pattern of CV_{NDVI} presents a high fluctuation distributed in the northwest of the study area and a low volatility distributed in the southeast (Fig. 4). Area with higher fluctuation is distributed mainly in the eastern of Bijie, the southern region of Zunyi and Guiyang cities; meanwhile, area with high fluctuation is concentrated in the northwest of study area. The regional NDVI in these areas exhibit large fluctuations. The distribution of NDVI is influenced by vegetation habitat and intensive human activities, particularly those conducted in regions with steep slope cultivation, deforestation in areas with severe soil erosion, and those that alter the ecological chain. The effect of environmental stress is strong, and this strong effect inhibits the growth of vegetation. Area with lower fluctuation is distributed mainly in non-karst landform areas of southeastern Kaili and Duyun. The above-mentioned analysis indicates that the spatial distribution of vegetation fluctuates in the local scales.

3.4 Variation trends of vegetation coverage

Trends of inter-annual NDVI change are divided into four levels according to Theil-Sen median trend analysis and Mann-Kendall test (Table 2). Vegetation coverage exhibits an overall increase trend (i.e., the region of increase area > decrease area). The regions with increased vegetation coverage account for 85.95%, whereas decreased regions only account for 14.06%. In terms of different geological backgrounds, vegetation coverage in karst area is increased to a higher degree than that in non-karst area. Regions where NDVI significantly increased (Fig. 5) are distributed mainly in Liupanshui, the west of Bijie, the northeast of Anshun, and in the eastern part of the Tongren city. Regions with insignificant increase are mainly observed in the northwest of study area, and these regions account for the largest proportion. Regions with insignificantly decreased vegetation coverage are distributed mainly in Zunyi, the south of Duyun and the southeast of study areas.

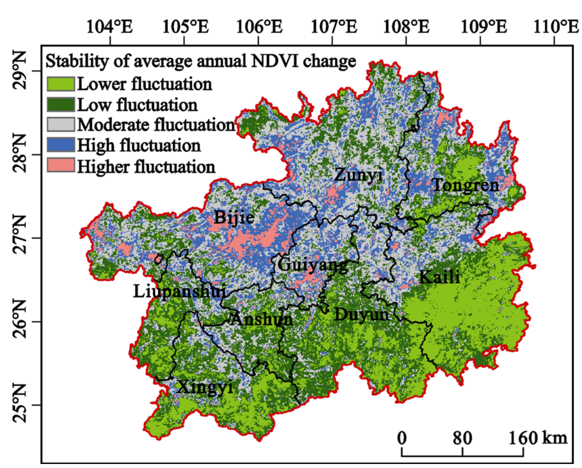

Fig. 4 Stability of average annual NDVI change in Guizhou Province of China from 1999 to 2015

Table 2 Changes of average annual NDVI in Guizhou Province of China from 1999 to 2015

Change	TS_{NDVI}	*Z* value	Area percentage (%)		
			Study area	Karst area	Non-karst area
Significant decrease	<0	>1.96	0.44	0.41	0.48
Insignificant decrease	<0	≤1.96	13.62	11.12	17.74
Insignificant increase	≥0	≤1.96	72.08	73.68	69.44
Significant increase	>0	>1.96	13.87	14.80	12.34

Note: TS is Theil-Sen median

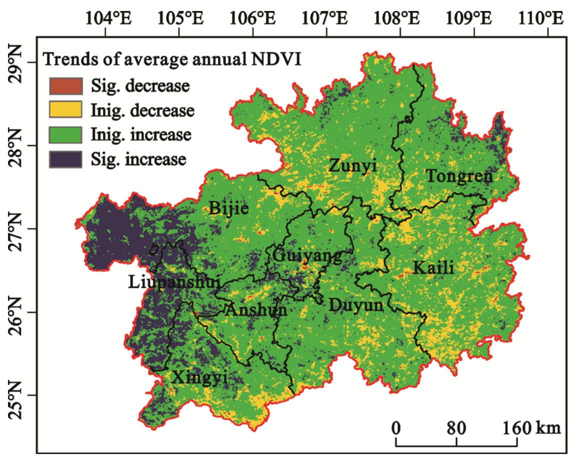

Fig. 5 Trends of average annual NDVI change in Guizhou Province of China from 1999 to 2015. Sig. is significant and in-sig. is not insignificant

Regions with significant decrease mainly lie in Kaili, Guiyang, Bijie, and Zunyi Cities.

Areas with significantly decreased vegetation coverage in different vegetation types from 1999 to 2015 (Fig. 6a) only account for a small proportion of the study area. Areas with insignificantly increased vegetation coverage are largest. Urban and built-up lands in significantly decreased areas have the largest proportion, followed by barren or sparsely vegetated lands. The proportion of lands with other vegetation types is less than 2.06%. In insignificantly decreased areas, the proportion of urban and built-up lands exceeds 37%, whereas the proportion of lands with different vegetation types is below 26%. The proportions of evergreen broadleaf forest and deciduous broadleaf forest fluctuate at approximately 21%, whereas the proportion of grasslands, croplands and barren or sparsely vegetated lands is only approximately 13%. In insignificantly increased areas, the proportion of urban and built-up lands is below 42%, that of areas with different vegetation types is between 64% and 79%, and that of closed shrublands reaches 79.55%. In significantly increased areas, grassland has the largest proportion, whereas evergreen broadleaf forest has the smallest proportion. In terms of different backgrounds (Figs. 6b and 6c), the proportions of significantly decreased vegetation types in karst and non-karst areas are consistent. The insignificantly decreased area with different vegetation types in non-karst area is higher than that in karst area, while the significantly increased area in non-karst area is lower than that in karst area.

3.5 Sustainability of vegetation cover variation

3.5.1 Hurst exponent of vegetation cover variation

The Hurst exponent varies significantly (Fig. 7a). The value ranges from 0.3476 to 0.9702, with the average value of 0.6591, and the standard deviation is 0.0533. The proportion of the unsustainability of average annual NDVI is 0.3957%, while that of sustainability sequence is 99.6042%. Areas with strong unsustainability, weak unsustainability, weak sustainability, and strong sustainability account for 0.0767%, 0.3191%, 74.6312%, and 24.9730%, respectively. The spatial distribution pattern of Hurst exponent of the normal distribution graphs is skewed to the unimodal right (Fig. 7b). The sustainability improvement trend of NDVI is more significant than that of the unsustainability trend, indicating that the overall trend of NDVI is continuously improving. The overall trend of Hurst exponent in Guizhou Province (Fig. 7a) is characterized by ′strong sustainability and weak sustainability exhibiting a concentrated pattern, while strong unsustainability and weak unsustainability present a scattered pattern′. In general, future vegetation coverage presents a continuous improvement trend that is more significant than that of the unsustainability trend.

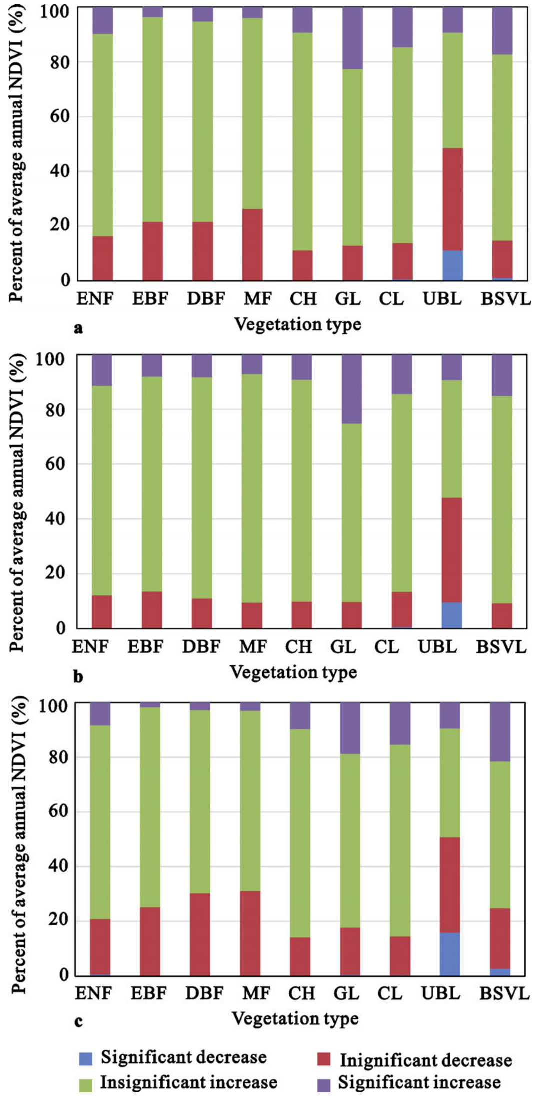

Fig. 6 Changes of average annual NDVI in different vegetation types in study area (a), karst area (b) and non-karst area (c) in Guizhou Province of China from 1999 to 2015. The codes of vegetation types can be seen from Fig. 1

The area showing strong sustainability is distributed mainly in Bijie, Guiyang, Liupanshui, the north of Zunyi, the east of Xingyi and the southeast of Anshun. The area with weak sustainability is represented through a flaky distribution particularly in south of Zunyi, the west of Tongren and Xingyi, and the north of Kaili. The area with strong unsustainability is distributed mainly in the southeast of Kaili. The vegetation conditions of weak unsustainability is distributed sporadically in the southeast of Kaili and scattered in the south of Duyun and the east of Tongren.

3.5.2 Sustainability of vegetation cover variation

The proportion of vegetation cover (Fig. 8, Table 3) with sustainable increase (91.43%) is more higher than that with sustainable decrease (1.14%). The areas with sustainable significant decrease account for 0.44%. These areas are distributed mainly in Guiyang, the south of Zunyi, the southeast of Bijie, and the east of Kaili, and are distributed sporadically in the southeast of Xingyi. The regions with sustainable insignificant decrease account for 0.70%, which are distributed mainly in Guiyang, Kaili, and the south of Zunyi, and are distributed sporadically in Xingyi City. The areas with sustainable insignificant increase account for 67.80% and are distributed mainly in the central and northeast parts of the study area. The regions with sustainable significant incerase account for 23.63%, which are distributed mainly in the western part of study area, including Liupanshui, the west of Bijie, the northeast of Xingyi, and the east of Tongren.

The sustainable increase of vegetation cover in karst area (91.22%) is more significant than sustainable decrease (0.78%), and the sustainable increase of vegetation

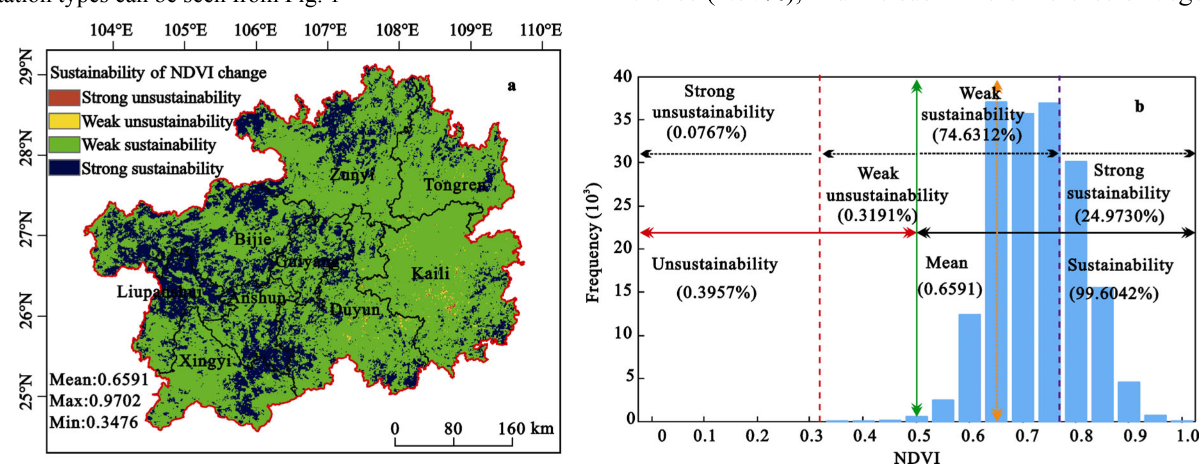

Fig. 7 Sustainability of average annual NDVI change (a) and normal distribution plot of the Hurst exponent (b) in Guizhou Province of China from 1999 to 2015

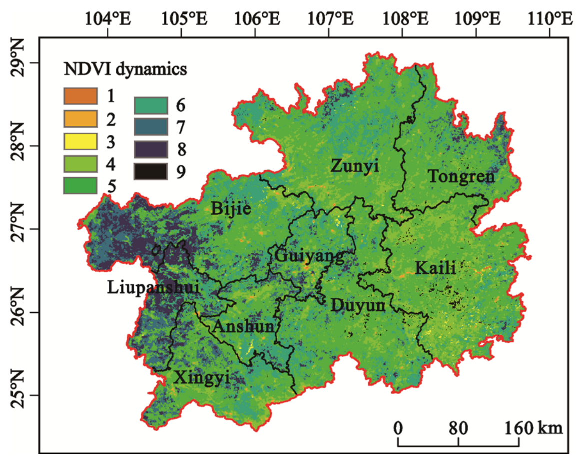

Fig. 8 Spatial distribution of average annual NDVI dynamics based on Theil-Sen median trend, Mann-Kendall test and Hurst exponent in Guizhou Province of China from 1999 to 2015. The sustainability classification can be seen from Table 3

cover in non-karst area (90.79%) is also more significant than sustainable decrease (1.72%). The regions with sustainable decrease, sustainable insignificant decrease, sustainable insignificant increase, and sustainable significant increase account for 0.22%, 0.56%, 66.53%, and 24.69% in karst area and account for 0.81%, 0.91%, 69.9%, and 20.89% in non-karst area, respectively.

3.5.3 Sustainability of vegetation cover in different elevations

The future trend of vegetation cover changes in different elevations (Fig. 9). The Hurst exponent exceeds 0.5 in different vegetation types in various altitudes. This result indicates that different elevations cause a persistent sequence. In particular, the Hurst exponent of NDVI ranges from 0 to 500 m, with average value of 0.7043. The variation exhibits a strong persistence. The main vegetation types in this altitude are croplands, grassland, closed shrubland, and evergreen needleleaf forest. Most of these areas are in the eastern part of non-karst area. Meanwhile, the Hurst exponent of NDVI in the elevation zone of 500–1000 m is lowest (i.e., 0.6945), and its main vegetation types are croplands, grasslands, closed shrublands, and evergreen needleleaf forest. This area mostly affected by human activities maybe the reason. Notably, human activities damage vegetation to a large extent. The Hurst exponent in the elevation zone of 1000–1500 m is relatively high (i.e., 0.6964). This typical geomorphic region is karst plateau. The vegetation at this altitude is strongly volatile, that is, easily degraded and easily improved. Land species are distributed mainly across this elevation range, and the Hurst exponent is easily affected by changes in the crop growth cycle. Implementing ecological construction projects (e.g., converting croplands into forests) promotes vegetation restoration in karst area. Deforestation and wood chopping (for firewood) damages the vegetation cover. The Hurst exponent in the elevation zone of 1500–2000 m exceeds 0.7126. The proportion of grasslands is relatively large, indicating that vegetation change trends of grasslands are stable. These high regions frequently have relatively steep slopes and are thus rarely disturbed by human activities. Simultaneously, forest conservation policies promote stability in high-altitude vegetation communities. Thus, elevation is an important factor in

Table 3 Statistical results of NDVI dynamics based on Theil-Sen median trend, Mann-Kendall tests and Hurst (*H*) exponent in Guizhou Province of China from 1999 to 2015

Code	Variation type	TS_{NDVI}	|*Z*| value	*H* exponent	Area percentage (%)		
					Study area	Karst area	Non-karst area
1	Strong sustainability and significant decrease	<0	>1.96	(0.75, 1.00]	0.40	0.20	0.73
2	Weak sustainability and significant decrease	<0	≤1.96	(0.50, 0.75)	0.04	0.02	0.08
3	Strong sustainability and insignificant decrease	<0	≤1.96	(0.75, 1.00)	0.40	0.39	0.40
4	Weak sustainability and insignificant decrease	<0	>1.96	(0.50, 0.75]	0.30	0.17	0.51
5	Weak sustainability and insignificant increase	>0	≤1.96	(0.50, 0.75]	13.05	10.83	16.70
6	Strong sustainability and insignificant increase	>0	>1.96	(0.75, 1.00]	54.75	55.70	53.20
7	Weak sustainability and significant increase	>0	>1.96	(0.50, 0.75]	17.20	17.90	15.04
8	Strong sustainability and significant increase	>0	≤1.96	(0.75, 1.00]	6.43	6.79	5.85
9	Undetermined future variation in trends	–	–	[0, 0.50]	7.43	8.01	7.50

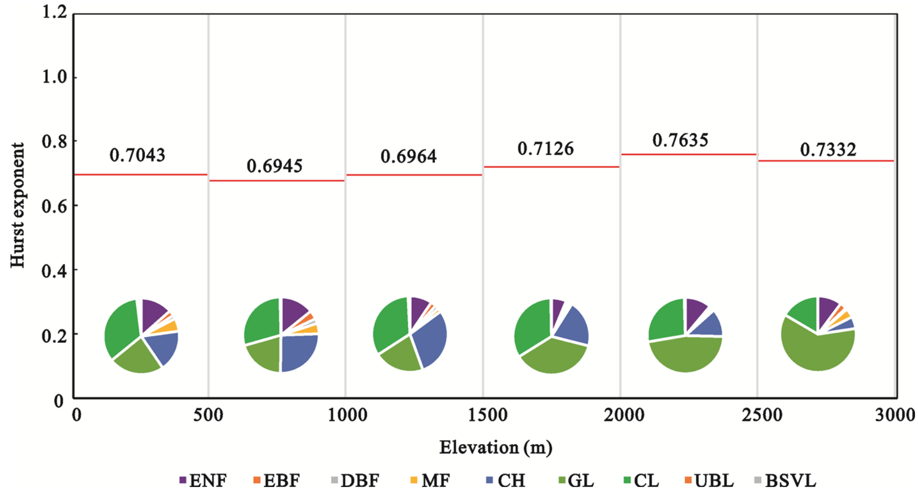

Fig. 9 Hurst exponent of average annual NDVI and its percentage for each elevation zone in different vegetation types in Guizhou Province of China from 1999 to 2015. The codes of vegetation types can be seen from Fig. 1

determining trends in vegetation changes. For sustainable improvement trends of vegetation NDVI in various altitudes, different vegetation types are inconsistent and an obvious threshold exists. A boundary is set at 2500 m in Guizhou Province. Below this line, the Hurst exponent increases with altitude. Vegetation exhibits a trend toward sustainable improvement, but the trend decreases above the boundary. The Hurst exponent reaches a maximum value (i.e., 0.7635) from elevations between 2000 and 2500 m.

4 Discussion

Satellite remote sensing is a useful method for detecting vegetation activities, which has been extensively applied in studying changes in terrestrial ecosystems. However, the results obtained are sometimes uncertain (Cao *et al.*, 2010). High plant saturation effects of NDVI covered in vegetation activity resulted in change in detection influence sensitivity (Li *et al.*, 2014). NDVI saturates in well-vegetated areas, especially in forest vegetation coverage, because of two reasons: one is as a result of saturation in the red channel and the other is due to the ratio-based NDVI equation (Wang *et al.*, 2003). The vegetation index (i.e., NDVI) derived from canopy reflectance in the red and near-infrared wavebands are useful indicators of canopy structure. NDVI is especially sensitive to differences in canopy cover in sparse canopies; it loses sensitivity in moderate and dense canopies (Gamon *et al.*, 1995). A large number of studies have proved that from grassland to shrubland and then to forest, the NDVI index has a weak response to vegetation characteristics (Gamon *et al.*, 1995; Boyd, 1999; Freitas *et al.*, 2005).

A spatial resolution of 1 km × 1 km with SPOT VGT remote sensing data is obtained in this study. However, guaranteeing that the pixels are the same is difficult, and the mixed pixel problem exerts a certain influence on the present study. Moreover, noise remains in the remote sensing data of the time series. A noise removal algorithm is ideal and must maximize de-noising while retaining the true value of metadata maximum noise-free pixels (Wang *et al.*, 2005). This study adopts a simple maximum value composite (MVC) method, which may not guarantee the complete removal of noise-like elements from NDVI data. The asymmetric Gauss algorithm, dual logic function fitting (double logistic), and the Savizky-Glolay method can be used to fit the time series data of vegetation. Therefore, high-resolution remote sensing data should be used to monitor heterogeneity vegetation, which is relatively strong in Guizhou Province. Simultaneously, a data-smoothing algorithm should be used to reconstruct time series data to original NDVI time series before monitoring vegetation.

This study employs a series of mathematical statistical methods to analyze the dynamic and quantitative vegetation changes in Guizhou Province from 1999 to 2015. Future vegetation trends are also analyzed. However, the focus may be on natural factors, e.g., temperature, precipitation, and human factors, e.g., rocky desertification engineering, land use and coverage changes (Xu *et al.*, 2013), human disturbance (Zhang *et al.*, 2014), that change vegetation cover. Natural factors have an obvious effect on vegetation cover changes. The spatial distribution of temperature and precipitation can affect the spatial distribution of vegetation in the study area and its pattern, and is thus ignored in this study. Therefore, future work should focus on the relationship between vegetation and climatic factors of key drivers by determining the influences of vegetation change and by statistically analyzing climatic factors and time lag among vegetation covers.

Moreover, human factors (i.e., converting farmlands into forests and grasslands) increase NDVI in Guizhou. Different statistical methods should be used to study the NDVI of the increased status in key areas wherein farmlands are converted into forests and grasslands with a slope classification (5º to 25º slope) as well as the effects of such conversions in Guizhou. This study should also collect statistics on the number of animals and on the area of grasslands and farmlands with regard to the contribution ratio of vegetation restoration in the study area. Finally, mathematical (residual sequence (Li, 2011)) models were constructed to establish regression equations and reveal the influence of human activities on vegetation. According to the residual sequence model obtained from the trend analysis, if the trend is positive, then the image element vegetation affected by human activities is improved. This condition indicates that the image element affects vegetation and disturbance variation. Thus, the quantitative relationship among vegetation cover, climate factors, and human activities should be investigated in future works.

5 Conclusions

In the present study, NDVI time series data from 1999 to 2015 are obtained based on the data set of SPOT VGT at a spatial resolution of 1-km and temporal resolution of 10-day. The coefficient of variation, Theil-Sen median trend analysis, and Mann-Kendall test are used to investigate the spatial-temporal changes of the vegetation cover and its future trend in Guizhou Province of Southern China. The main conclusions are as follows:

(1) Spatial distribution pattern of vegetation cover is high in the east whereas low in the west in Guizhou Province, and average annual NDVI is 0.5742. Average annual NDVI from west to east (0.5346) is higher than that from south to north (0.5314).

(2) Average annual NDVI improved progressively during the study period. The growth rate of average annual NDVI is 0.028/10 yr, which is slower than that of vegetation in Southwest China (0.054/10 yr) from 1998 to 2012 and in the country (0.048/10 yr) from 1998 to 2007. Average annual NDVI increases in un-synchronization under different geological backgrounds. The growth rate of NDVI in karst area is faster than that in non-karst area.

(3) Vegetation coverage in the study area is stable overall, but fluctuates in the local scales. Areas with high and higher volatility in karst area are larger than that in non-karst area. This difference is due to that the vegetation in karst area is more sensitive and discrete than that in non-karst area.

(4) Vegetation cover continues to exhibit an overall increase trend. The regions with increased vegetation coverage account for 85.95%, whereas decreased regions only account for 14.06%. The Hurst exponent of NDVI in different vegetation types has an obvious threshold in various elevations.

(5) The proportion of vegetation cover with sustainable increase is higher than that of vegetation cover with sustainable decrease. The improvement in vegetation cover may expand to most parts of the study area in future.

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