SPATIAL-TEMPORAL CHANGE PATTERNS OF VEGETATION AND THE INFLUENCE OF CLIMATIC FACTORS IN YUNNAN PROVINCE, CHINA FROM 2000 TO 2020

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Abstract. Vegetation is extremely important for the ecosystem, it is an important link that connects soil, organisms, and the atmosphere. As plants perform photosynthesis, carbon cycle and energy ex-change, they play a balancing role for global ecological changes. Based on the datasets of MODIS Normalized Difference Vegetation Index (NDVI) and the daily meteorological data from 25 weather stations in Yunnan province, China, the spatial and temporal distribution characteristics of NDVI over a 21-year-period were studied, and the response relationship between NDVI and climate factors. The monthly and yearly spatial distribution pattern of NDVI was further explored using the standard deviational ellipse. Besides, the changing trend, stability, and characteristics of the future changing trend of the vegetation NDVI were evaluated through Sen+MK, coefficient of variation, and the Hurst index in Yunnan province, China. A partial correlation analysis was carried out using the NDVI data based on the temperature and precipitation from 2000 to 2020. The center of gravity of Yunnan is mainly from south-west to north-east, and the trend for the NDVI during the past 21 years mostly improved. However, in the future, the vegetation may follow the trend of degradation, and the study area is more affected by temperature. In recent years, the average temperature throughout the world has been on the rise due to global warming, which has elicited the response of vegetation to climate change in advance. The vegetation in Yunnan is showing an increasing trend, Moreover, it is particularly important to protect the ecological environment in the protected region.
Keywords: *climate change, future trends, spatial-temporal changes of NDVI, stability analysis, trend analysis*

Introduction

With climate change, urban sprawl, and the expansion of human activity areas, the growth of global vegetation has been seriously affected (Chu et al., 2019; He et al., 2021). Vegetation is extremely important for the ecosystem. The quality of vegetation directly affects the balance of the ecosystem and plays an important role in moderating climate and hydrological and biological cycles within the earth system (Goetz et al., 2005; Zhu et al., 2020). Scientists have started focusing on the relationship between vegetation and climate due to the deterioration of the ecosystem. Among all the driving factors that may influence vegetation growth, temperature and precipitation have been studied most frequently, and they are proved to be closely related to the changes of vegetation condition (Zhang et al., 2015, 2020). The precipitation determines the quality of the environment in which plants grow in a region, and temperature determines the diversity of plant and animal species in a region and is an important factor in determining the direction of regional ecological development (Mortsch, 1998; Li et al., 2017). An assessment of more than 4,000 species globally found that spring phenology was advanced for about 2/3 of species, driven by regional climate change (Parmesan et al., 2015). A global warming of 1.5°C would expose marine ecosystems and their coasts to a moderate to very high risk of biodiversity loss, with a doubling of the risk of extinction of endemic species in biodiversity hotspots; A warming of 3°C would put most marine and coastal ecosystems at very high risk of biodiversity loss (Kerr, 2007; Hoegh-Guldberg et al., 2019; Freychet et al., 2022). Therefore, It is important to assess the relationship between vegetation and climate change. This would be beneficial for maintaining terrestrial ecosystems under a changing environment.

Indeed, vegetation indices based on remote sensing are crucial for analyzing large-scale vegetation changes (Kang et al., 2020). The Normalized Difference Vegetation Index (NDVI) is considered to be a good indicator of vegetation greenness and activity (Yang et al., 2020). NDVI has been extensively used to show the level of vegetation coverage and growth status (Chu et al., 2021), as it is sensitive to vegetation growth, can directly reflect the vegetation growth status. Almost all earth observation satellites are equipped with sensors that can generate this index at different spatiotemporal resolutions. The NDVI has since become the dominant index for vegetation research because of its long-term data series, simplicity, and ease of use (Liu et al., 2018; Ma et al., 2021; Peng et al., 2021). Recently, many scientists have carried out various studies into the long-time trend series, patterns of NDVI at large scales, and the relationship between NDVI and climatic factors (Li et al., 2014; Zhang et al., 2017; Zhang, 2020). The precipitation and temperature are the two climatic factors affecting the vegetation growth status (Gao et al., 2018; Xiao et al., 2020; Wang et al., 2021). One study (Xiong et al., 2018) showed that the vegetation coverage had a significant trend in growth within time and space based on the MODIS NDVI datasets in Yunnan Province from 2001 to 2016. The results of the analysis of vegetation index (NDVI)in the Western Sichuan Plateau showed an upward trend during the past 17 years. NDVI was positively correlated with temperature and negatively correlated with precipitation (Xie et al., 2020). In the Loess Plateau, both temperature and precipitation had significant effects on the vegetation index (NDVI), but their combined effects on the vegetation index (NDVI) were stronger (Dong et al., 2020). The positive correlation between the vegetation index (NDVI) in Shannxi province and the average annual temperature was greater than the influence of precipitation on NDVI (Daurina, 2019).

Considered as the province with the largest number of plant species in China, Yunnan is called the "plant kingdom". In recent years, in Yunnan Province, the construction of ecological civilization has been considered as a key breakthrough in the layout of the "five-sphere integrated plan", and the protection of biodiversity and conversion of farmland have been actively provided. The measures promoting eco-environments such as rehabilitating forests and grasses and protecting and managing plateau lakes have been adopted (Lu et al., 2020; Xiong et al., 2021). Therefore, based on MODIS datasets and

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temperature and precipitation data from 25 weather stations, as well as the trend analysis methods of Sen + MK (Theil-Sen Median + Mann-Kendall), the coefficient of variation, Hurst index, and partial correlation analysis were carried out to monitor the temporal and spatial variations of the vegetation index and the relationship between the vegetation index (NDVI) and climatic factors in Yunnan Province during the past 21 years.

Materials and methods

Study area

Yunnan Province is located in southwestern China from 21°8′-29°15′N to 97°31′-106°11′E (*Fig. 1*). It is a low-latitude inland area with a mountainous plateau. Yunnan has a subtropical and tropical monsoon climate, with a total area of 39.41 × 10^4 km^2. It is connected to the east by Guizhou Province and Guangxi Province, to the north by Sichuan Province, to the northwest by Tibet Autonomous Region, to the west by Myanmar, and the south by Laos and Vietnam. It has low elevations in the southeast and gradually descends from north to south, forming a mountain plateau topography.

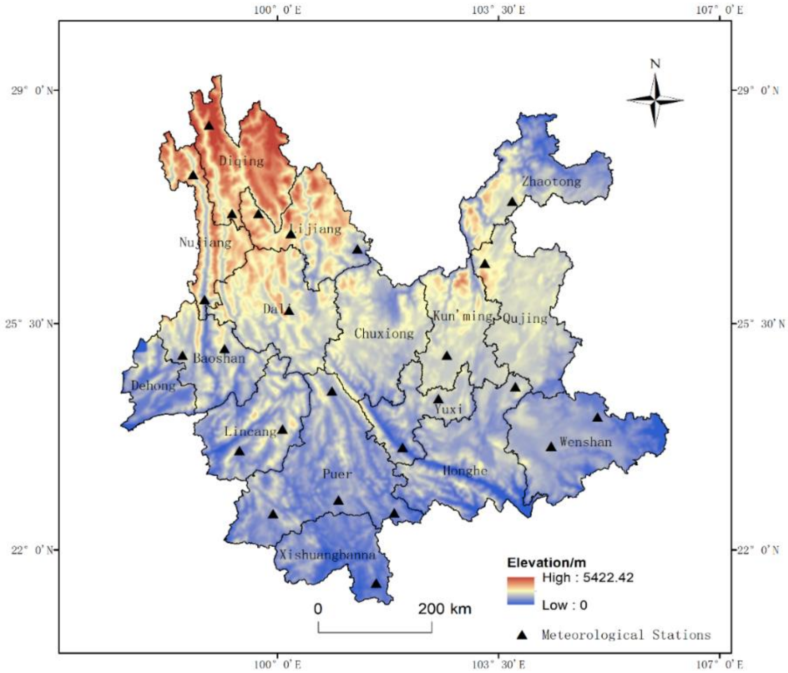

Figure 1. *Meteorological stations in this study area*

Data sources and analysis method

The MODIS data (MOD13Q1) used in this study were generated from NASA during the 2000-2020 period, with a spatial resolution of 250 meters and a time resolution of 16d (http://ladsweb.modaps.eosd is.nasa.gov/search/). The data were preprocessed by MODIS Reprojection Tool (MRT) through splicing, projection, and format conversion steps. The maximum value synthesis method (MVC) was used to reduce the influence of the clouds, atmosphere, and solar altitude angles and synthesize the monthly NDVI data as well as the annual NDVI data based on the monthly data using the average method. The data used were the daily meteorological data from 25 weather stations in Yunnan

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Province from 2000 to 2020. Data were obtained from the China Meteorological Data Network (http://data.cma.cn/), and the meteorological data were projected through ArcGIS and obtained by resampling the NDVI Raster data with meteorological factors and the same resolution.

Methods

Standard deviational ellipse

The standard deviational ellipse is a spatial statistical method that characterizes the spatial distribution of geographic elements from many aspects. It has been widely used in various fields, including ecology, geography, economics, and demography (Fu and Zhou, 2015; Bai et al., 2021). With barycentric coordinates, the semi-major axis, the semi-minor axis, and the azimuth angle as parameters, the spatial distribution characteristics of the entire study area were analyzed. In this study, the barycentric coordinates were used to describe the relative position of NDVI and further the overall offset of NDVI. Moreover, the semi-major axis and the semi-minor axis were used to describe the directionality and dispersion of NDVI, respectively, while the azimuth angle could characterize the spatial direction of the NDVI trend. The equations are as follows (Zhao and Zhao, 2014):

$$SDE\ (\bar{x},\bar{y}) = \left(\sqrt{\frac{\sum_{i=1}^{n}(w_i x_i-\bar{X})^2}{w_i}},\sqrt{\frac{\sum_{i=1}^{n}(w_i y_i-\bar{Y})^2}{w_i}}\right) \quad \text{(Eq.1)}$$

$$\tan\theta = \frac{\left(\sum_{i=1}^{n} w_i^2\hat{x}_i^2-\sum_{i=1}^{n} w_i^2\hat{y}_i^2\right)+\sqrt{\left(\sum_{i=1}^{n} w_i^2\hat{x}_i^2-\sum_{i=1}^{n} w_i^2\hat{y}_i^2\right)^2+4\sum_{i=1}^{n} w_i^2\hat{x}_i^2\hat{y}_i^2}}{2\sum_{i=1}^{n} w_i^2\hat{x}_i\hat{y}_i} \quad \text{(Eq.2)}$$

$$S\sigma_x = \sqrt{\frac{\sum_{i=1}^{n}(w_i\hat{x}_i\cos\theta-w_i\hat{y}_i\sin\theta)^2}{\sum_{i=1}^{n} w_i^2}} \quad \text{(Eq.3)}$$

$$\sigma_y = \sqrt{\frac{\sum_{i=1}^{n}(w_i\hat{x}_i\sin\theta-w_i\hat{y}_i\cos\theta)^2}{\sum_{i=1}^{n} w_i^2}} \quad \text{(Eq.4)}$$

where $SDE\ (\bar{x},\bar{y})$ are barycentric coordinates, w_i is the weight, and θ is the azimuth, while $\hat{x}_i$ and $\hat{y}_i$ are the mean center and deviation of coordinates, respectively, and σ_x and σ_y are the standard deviation of the x-axis and y-axis, respectively.

Trend analysis

The Theil-Sen Median slope estimator and the Mann-Kendall statistical test were used for trend analysis (Jiang et al., 2015). The Sen+MK method is not sensitive to errors and outliers; thus, it is not necessary to obtain time series and linear data with the normal distribution. This is the reason why this method is widely used in trend analysis for analyzing extensive time-series data. The equations are as follows:

$$\beta = Median\left(\frac{x_j-x_i}{j-i}\right), \forall j > i \quad \text{(Eq.5)}$$

where 1<i<j<n； x_j and x_i are the values of the jth item and the ith item in the NDVI time-series data, respectively. β is the slope, and $\beta > 0$ indicates that the NDVI time series

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show an improved trend. Moreover, when $\beta < 0$, it indicates the degradation of NDVI time series.

Mann-Kendall is a non-parametric statistical test method, which was first proposed and used by Mann and further improved by Kendall. Since the Theil-Sen Median slope estimator cannot determine the significance of the trend in the NDVI time series, the Mann-Kendall test method was used for this purpose. The statistic S in the Mann-Kendall test was calculated as follows:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(x_j - x_i) \quad \text{(Eq.6)}$$

where,

$$sgn(x_j - x_i) = \begin{cases} 1 & x_j - x_i > 0 \\ 0 & x_j - x_i = 0 \\ -1 & x_j - x_i < 0 \end{cases} \quad \text{(Eq.7)}$$

Since the length of time series was n = 21 during the 2000–2020 period, and the statistic S had a standard normal distribution, the Z-test statistic was used for trend testing. Moreover, Z was used as the attenuation index of NDVI. The equations are as follows:

$$Z = \begin{cases} \frac{S-1}{\sqrt{VAR(S)}} & S > 0 \\ 0 & S = 0 \\ \frac{S+1}{\sqrt{VAR(S)}} & S < 0 \end{cases} \quad \text{(Eq.8)}$$

$$VAR(S) = \frac{n(n-1)(2n+5)}{18} \quad \text{(Eq.9)}$$

where x_j and x_i are the values of the jth item and the ith item in the NDVI time-series data, respectively. N is the length of the time series, and Sgn is the symbol for the signum function. The $|Z|$ values corresponding to different confidence levels, greater than 1.65, 1.96, and proofread 2.58 indicate that the trend has passed the significance test with the confidence levels of 90%, 95%, and 99%, respectively. In this study, the values of $\alpha = 0.05$ and $Z_{1-\alpha} = Z_{0.975} = 1.96$ were used. When $|Z| > Z_{1-\alpha}$ it indicates that the NDVI time series follow a significant changing trend. $|Z| \leq Z_{1-\alpha}$, it indicates that the NDVI time series showed a weakly significant changing trend.

Analysis of future trends

The future trend of NDVI in Yunnan Province was obtained by calculating the Hurst index based on the R/S estimation and combining the results of the trend analysis based on Theil-Sen Median (Zhang and Ren, 2011; Peng et al., 2012). It has also been used for trend analysis of remote sensing inversion indices and has confirmed the effectiveness for portraying consistency of time series in vegetation indices such as NDVI (Peng et al., 2012; Kalisa et al., 2019). The time series of the image values of a single pixel, whose length is n, will be divided into several subseries X(τ) according to different lengths of sublists (1,2,…,τ), where τ denotes the length of the sublist.

Calculate the mean value of each sublist in each subseries:

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$$X_{\text{mean},\tau} = \frac{1}{\tau}\sum_{i=1}^{n} X(\tau), \tau = 1,2,...,n \quad \text{(Eq.10)}$$

Calculate the cumulative deviation of each subseries:

$$D(\tau,t) = \sum_{i=1}^{t}(X(i) - X_{mean,\tau}), 1 \le t \le \tau \quad \text{(Eq.11)}$$

Calculate the standard deviation sequence of all sublists in each subseries:

$$S(\tau) = \sqrt{\frac{1}{\tau}\sum_{i=1}^{\tau} X(i) - X_{mean,\tau}^{2}}, \tau = 1,2,...,n \quad \text{(Eq.12)}$$

Compute the range sequence of each subseries:

$$R = \max_{1\le t\le\tau} D(\tau,t) - \underset{1\le t\le\tau}{mi}\, D(\tau,t), \tau = 1,2,...,n \quad \text{(Eq.13)}$$

Calculate the rescaled range of each subseries (R/S):

$$\frac{R(\tau)}{S(\tau)} = (c\tau)^{H} \quad \text{(Eq.14)}$$

Calculate the logarithm of Equation:

$$\ln\frac{R(\tau)}{S(\tau)} = H\ln\tau + H\ln c \quad \text{(Eq.15)}$$

The Hurst index has the three following functions: when $0 < H < 0.5$, the future trend is opposite the past, indicating that the increasing trend in the past will decrease in the future, and vice versa. When $H = 0.5$, the change in trends is random with no correlation. The $0.5 < H < 1$ indicates that the future changing trend is consistent with the changing trend in the past (the increasing trend in the past will also increase in the future). Combining the Hurst exponent analysis with the linear regression results, we were able to conclude the consistency of vegetation changes (*Table 1*).

Table 1. *Assessment of future vegetation change types using SEN+MK results and Hurst index*

β(Trend)	Hurst index	Type of future change
β>0.002	0<H<0.5	Future degradation
β>0.002	0.5<H<1	Continuous improvement
-0.002≤β≤0.002	0<H<0.5	Remain stable
-0.002≤β≤0.002	0.5<H<1	
β<-0.002	0<H<0.5	Future improvement
β<-0.002	0.5<H<1	Continuous degradation

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Coefficient of variation analysis

The coefficient of variation (CV) reflecting the degree of the difference in the NDVI time-series data indicates the stability of the inter-annual variation in the NDVI data.

$$CV = \frac{1}{\overline{NDVI}} \times \sqrt{\frac{\sum_{i=1}^{n}(NDVI_i - \overline{NDVI})^2}{n-1}} \quad \text{(Eq.16)}$$

where CV is the coefficient of variation, and n is the length of the NDVI time series. $NDVI_i$ is the value of NDVI in the ith year, and $\overline{NDVI}$ is the average NDVI during the n years. The larger the CV value, the larger the data fluctuation.

Partial correlation analysis

Partial correlation is the analysis of the degree of correlation between two variables without considering the influence of the third. There are many factors influencing vegetation. This study focused on temperature and precipitation. As the analysis of the correlation between two factors is performed, the influence of other factors is required to be excluded. A partial correlation analysis was carried out using the NDVI data based on the temperature and precipitation from 2000 to 2020. The equations are as follows (Zhang et al., 2014):

$$r_{xy,z} = \frac{r_{xy} - r_{xz}r_{yz}}{\sqrt{(1 - r_{xz}^2) + (1 - r_{yz}^2)}} \quad \text{(Eq.17)}$$

where $r_{xy,z}$ is the partial correlation coefficient between the dependent variable x and the independent variable y after the independent variable z is fixed. r_{xy},r_{xz}, and r_{yz} are the correlation coefficients of the variables x and y, x and z, and y and z, respectively.

Results

Temporal and spatial characteristics of NDVI in Yunnan province

Spatial-temporal characteristics of vegetation in Yunnan Province within one year

To study the monthly changes in the vegetation in Yunnan Province during the past 21 years, the monthly average NDVI values from 2000 to 2020 were calculated (*Fig. 2*), the average annual NDVI in Yunnan Province over the past 21 years is 0.616. Results showed that these values increased with a "W"-shaped recovery, and the growth rate was 0.145/10a ($P < 0.001$), of which only the values for five months from August to December were greater than the average, while in the remaining months, they were lower. In general, the trend was downward from January to March, followed by a gradual rise in May. Due to the precipitation hysteresis, the temperature was high, with low rain fall in June. The rainy season began in mid-to-late June, with a trough in June, and the NDVI value reached its lowest (0.463). There was a substantial increase in this value from June to October, which may be during the period of plant growth, and the maximum value of NDVI reached 0.715 in September. The plants (vegetation) then entered winter and began to wither, and the NDVI value decreased accordingly.

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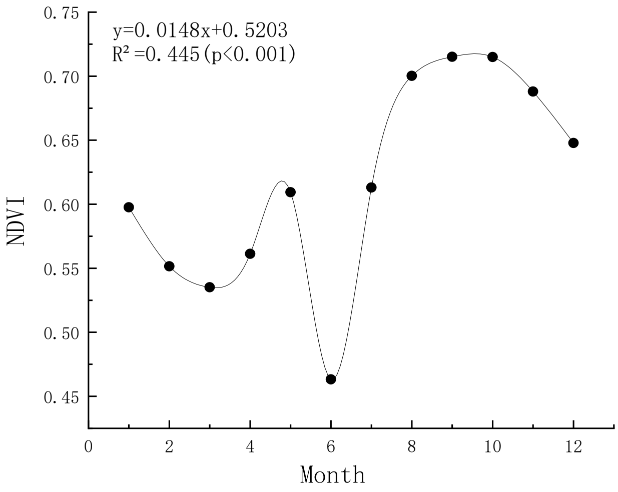

Figure 2. *The monthly average NDVI in Yunnan Province from 2000 to 2020*

The spatial distribution characteristics of NDVI were described over time based on the monthly spatial-temporal changes in Yunnan Province. Based on the results of the spatial distribution of NDVI, the standard deviational ellipse method was used to further analyze the directional featuresof the dynamic evolution of NDVI. The results of the analysis of the standard deviational ellipse showed that the weight on monthly NDVI lied in Chuxiong City (*Fig. 3*). From February to July, the barycenter moved 40.11 kilometers to the northeast, and from July to December, it moved 36.92 kilometers to the south-west. The barycenter shifted in the opposite direction from February to July and July to December. Based on the coordinate azimuth, it dropped from 108.97° in February to 99.59° in July, followed by a rise to 108.91° in December, showing an overall gradual trend of decline to rise. In general, the directional characteristics of the center of gravity migration model in this study area were obvious, indicating that the spatial distribution pattern in this study area mainly extends in the northeast-southwest direction.

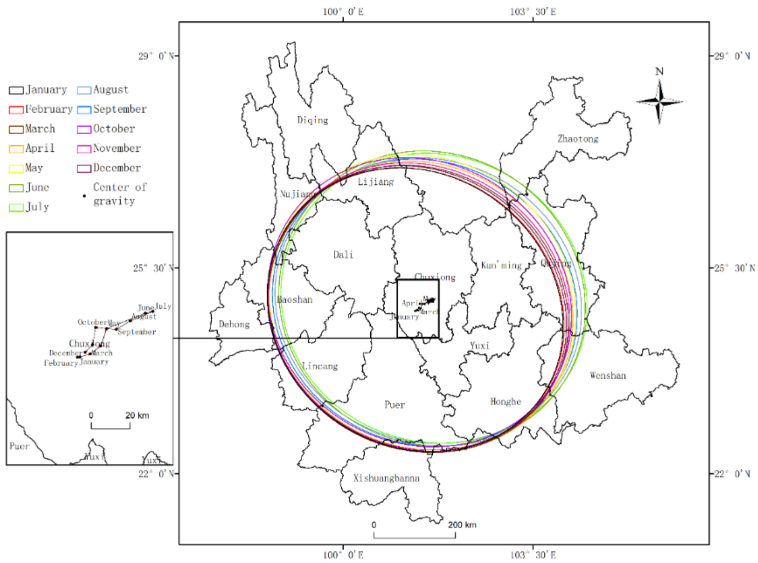

Figure 3. *Standard deviational ellipse for the monthly distribution of NDVI in Yunnan Province from 2000 to 2020*

Annual spatial-temporal characteristics of vegetation in Yunnan Province

The interannual changes inthe vegetation index (NDVI) from 2000 to 2021 in Yunnan Province were analyzed. The NDVI in this study showed a fluctuating upward trend. The rate of increase was 0.033/10a ($P < 0.001$). The average NDVI in Yunnan Province during the past 21 years was 0.614. The lowest value was 0.513 in 2000, while the highest was 0.608 in 2019. This average value was greater than the inter-annual average values in 2006, 2009, 2011, 2013, and 2015–2020. NDVI fluctuated significantly from 2000 to 2012, and the upward trend of NDVI from 2012 to 2020 was relatively rapid (*Fig. 4*).

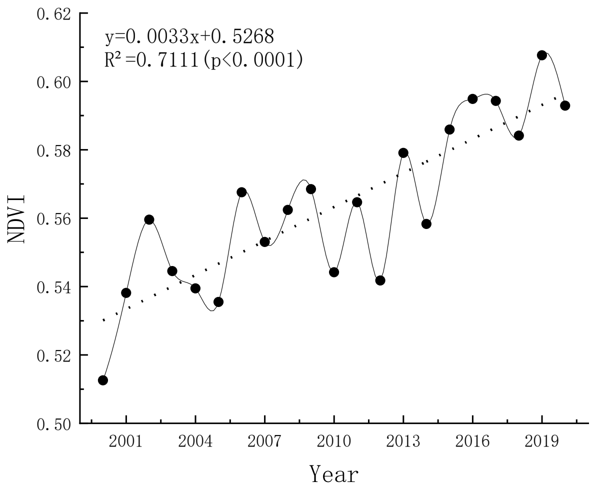

Figure 4. *Annual changes of NDVI in Yunnan Province from 2000 to 2020*

Based on spatial distribution characteristics, the vegetation pattern decreased from the south-west to the northeast (*Fig. 5*). High NDVI values were mainly observed in Xishuangbanna Dai Autonomous Prefecture, Puer City, Lincang City, the Prefecture of De Hong, and the south of Honghe Autonomous Prefecture. That is due to the rapid development of Kunming, Qujing, and the eastern part of Yuxi in recent years, and the human activity areas have expanded, which has led to a decline in vegetation.

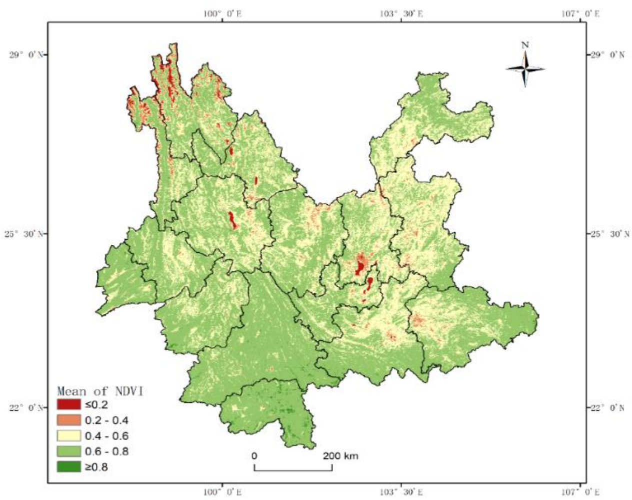

Figure 5. *Distribution of mean values of NDVI in Yunnan Province from 2000 to 2020*

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The analysis of standard deviational ellipse (*Fig. 6*) showed that the annual NDVI barycenter in the study area was mainly distributed in Chuxiong Yi Autonomous Prefecture, Chuxiong City. The movement of NDVI barycenter in Yunnan Province during the last 21 years was stable, and the offset distance was short. The barycenter of the vegetation index (NDVI) shifted southward by 6.5 kilometers over the past 21 years. During 2000–2012, the barycenter movement showed repetition in Yunnan Province. The shift from 2000 to 2003 was not profound, and the shift from 2003 to 2005 was toward the northeast, while it was toward the northwest from 2006 to 2011. In 2012, the barycenter almost returned to its position in 2000. From 2011 to 2000, due to the significant improvement of the vegetation coverage in the south of Yunnan, the barycenter shifted southward, with the direction of the south-west to the northeast.

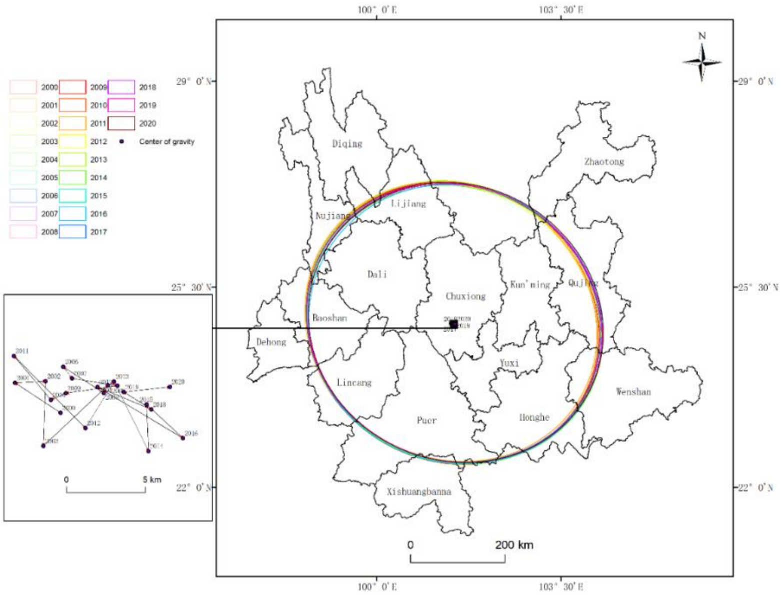

Figure 6. *Standard deviational ellipse describing the distribution of annual NDVI in Yunnan Province from 2000 to 2020*

Analysis of the vegetation index (NDVI) trend in Yunnan Province

Based on the MOD13Q1 data from 2000 to 2020 and the Theil-Sen median slope (*Fig. 7a*), the improved NDVI trend of vegetation in Yunnan Province was obtained (*Fig. 7b and Table 2*). The areas of improvement accounted for 64.48%, including 48.92% significant increase and 15.56% weakly significantly increase. The areas with significant increase were mainly located in the east of Yunnan Province, in Qujing City and Wenshan Prefecture, Zhaotong City. Areas with insignificant change were in different locations. The stable regions accounted for 29.79%, mainly distributed in the northwest Yunnan Province, Diqing, Nujiang, and Dali Prefecture. There were few areas with a disturbing trend in Yunnan Province, of which significant and weakly significantly degrade areas accounted for 3.04% and 2.69%, respectively, located in different cities in Yunnan Province (*Fig. 7 and Table 2*).

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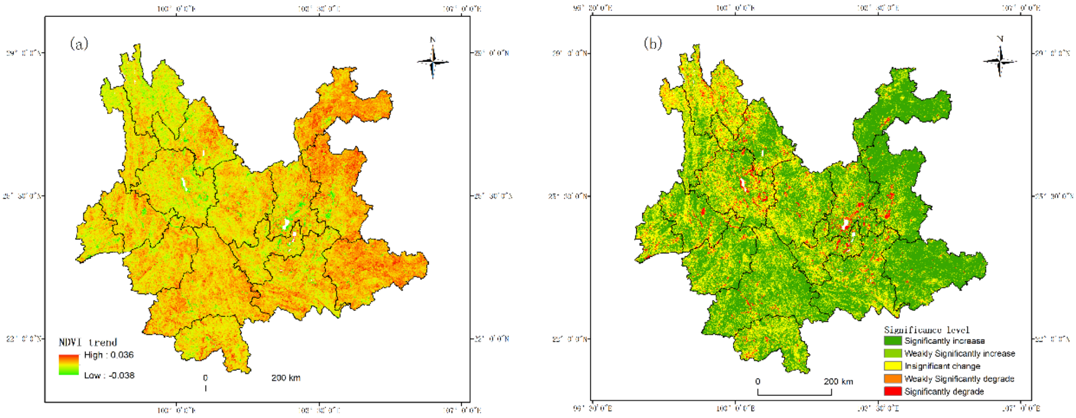

Figure 7. *Change types and trends of NDVI in Yunnan Province from 2000 to 2020*

Table 2. *Statistics of the vegetation index (NDVI)trends in the Yunnan Province*

β (Trend)	|Z| (Statistics)	Change type	Area proportion
β>0.002	|Z|>1.96	Significantly increase	48.92%
β>0.002	|Z|≤1.96	Weakly significantly increase	15.56%
-0.002≤β≤0.002	|Z|>1.96	Insignificant change	29.79%
-0.002≤β≤0.002	|Z|≤1.96		
β<-0.002	|Z|≤1.96	Weakly significantly degrade	2.69%
β<-0.002	|Z|>1.96	Significant degrade	3.04%

Future trends of the vegetation index (NDVI) in Yunnan Province

Along with the Sen+MK analysis, the Hurst index analysis was carried out on the vegetation index (NDVI) of Yunnan Province during the past 21 years (*Fig. 8a*). The spatial distribution of the Hurst index was obtained, and the Hurst index was coupled with the trend analysis. The average value of the Hurst index was 0.43, and the index distribution was between 0.08 -1. Results showed the main anti-sustainable future changes in vegetation in Yunnan Province. The area that will continue to improve in the future accounted for 15.05% of the total area, mainly in the south of Wenshan Prefecture, Qujing City. In the future, 29.80% of the total area, mainly in Diqing, Nujiang, Dehong, and Dali Prefecture, will remain stable. The area with the degradation trend in the future accounted for 49.42%, distributing throughout the research area, mainly in the north of Zhaotong City, Pu'er City, and Qujing City (*Fig. 8b and Table 3*). The area, which continues to degrade in the future accounted for 2.55%, distributing in the whole study area, indicating that the vegetation in Yunnan Province may follow a trend of degradation.

Analysis of the stability of the vegetation index (NDVI) in Yunnan Province

From 2000 to 2020, the coefficient of variation (CV) of vegetation NDVI in Yunnan Province was 0.018–1.228, with an average of 0.080. In general, the stability of NDVI in Yunnan Province has been relatively low during the past 21 years. Based on the coefficient of variation and the actual situation of the study area, using the Jenks method, the area was divided into lower fluctuation change area, low fluctuation change area, medium fluctuation change area, high fluctuation change area, and higher fluctuation

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change area, accounting for 47.40%, 42.07%, 8.71%, 1.57%, and 0.25%, respectively. The high fluctuation change area was near plateau lakes in Yunnan Province and high-altitude areas in Diqing and Nujiang prefectures (*Fig. 9*).

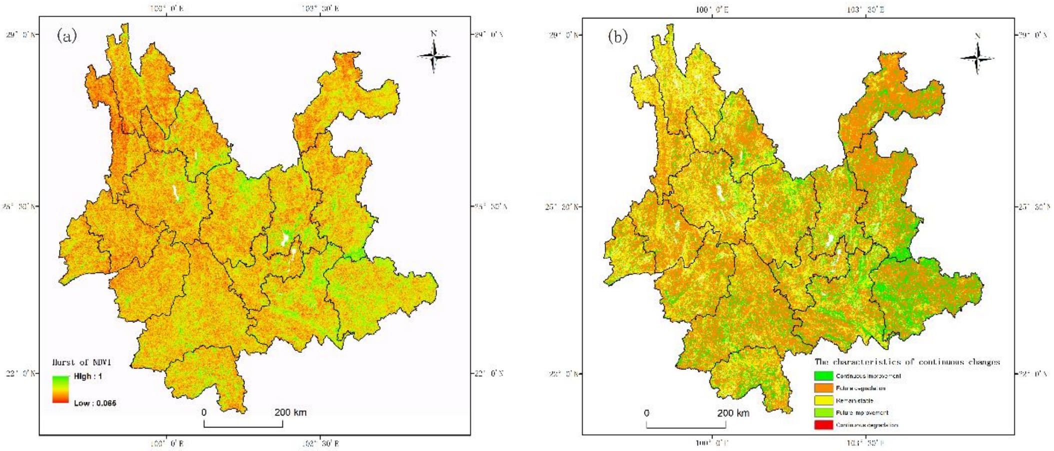

Figure 8. *The Hurst index of vegetation NDVI and characteristics of continuous changes in Yunnan Province from 2000 to 2020*

Table 3. *Statistical characteristics of continuous changes in the vegetation index (NDVI) in Yunnan Province*

β (Trend)	Hurst index	Type of future change	Area proportion
β>0.002	0<H<0.5	Future degradation	49.42%
β>0.002	0.5<H<1	Continuous improvement	15.05%
-0.002≤β≤0.002	0<H<0.5	Remain stable	29.80%
-0.002≤β≤0.002	0.5<H<1		
β<-0.002	0<H<0.5	Future improvement	3.18%
β<-0.002	0.5<H<1	Continuous degradation	2.55%

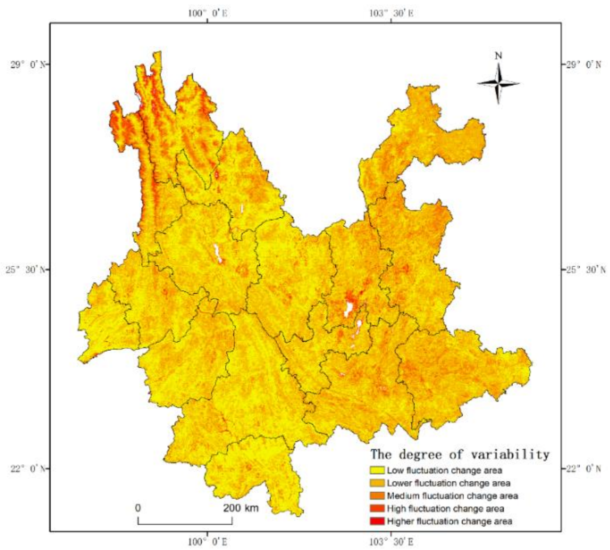

Figure 9. *The degree of variability of the vegetation index (NDVI) in Yunnan Province from 2000 to 2020*

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Analysis of the response of vegetation NDVI to climate factors in Yunnan Province

Analysis of the interannual variation in climate factors

Climatic factors had a great effect on vegetation growth. This study looked at climate factors at temporal and spatial scales to determine the degree of correlation between vegetation NDVI and two climate factors. The temperature and precipitation were mainly influenced by the climatic zone in Yunnan Province. The south-west of Yunnan Province has a tropical and subtropical climate, and the temperature and precipitation were higher in the south-west; this is the reason why they decreased from the south-west to the northeast. The characteristics of variation in average annual precipitation, average annual temperature, and average annual NDVI value in Yunnan Province from 2000 to 2020 were evaluated (*Fig. 10 and Fig. 11*). The annual average temperature had an upward trend at a rate of 0.928 °C/10a, and the average temperature during the past 21 years was 16.77 °C. The annual precipitation decreased at a rate of 39.6 mm/10a, and the average annual precipitation was 1068.24 mm. There was no significant trend for each year, and the precipitation fluctuated strongly. NDVI was positively correlated with temperature. The precipitation showed an upward trend, with an increase in the previous year and an increase in NDVI in this year. The impact of temperature on the vegetation NDVI was stronger than on precipitation.

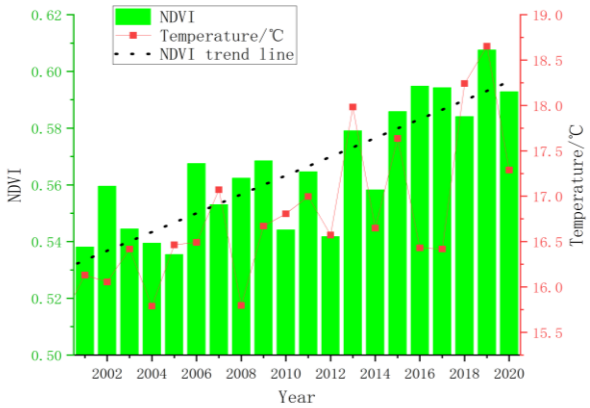

Figure 10. *Characteristics of NDVI and changes in the annual average temperature in Yunnan Province from 2000 to 2020*

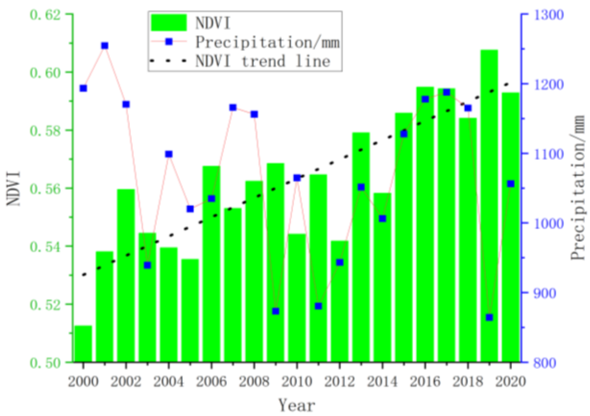

Figure 11. *Characteristics of NDVI and changes in the annual average precipitation in Yunnan Province from 2000 to 2020*

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Analysis of the response characteristics of vegetation NDVI to temperature and precipitation

The partial correlation analysis of vegetation NDVI, precipitation, and temperature was carried out to further determine the degree of influence of temperature and precipitation during the past 21 years, the NDVI and temperature bias correlation coefficients were -0.908-0.877 (*Fig. 12a*) and the NDVI and precipitation bias correlation coefficients were -0.882-0.931 (*Fig. 13a*). Results showed that NDVI was positively correlated with temperature, with the positively correlated area accounting for 81.06%, indicating that most areas were affected by temperature to improve vegetation NDVI, while the area exhibiting a negative correlation accounted for 18.94% (*Fig. 12b and Fig. 13b)*. In this study, the area in which the vegetation NDVI was significantly correlated with temperature (P< 0.05) accounted for 13.53%, of which the area exhibiting a significant positive correlation accounted for 12.80%, mainly distributed in Zhaotong City and the east of Wenshan Prefecture. Zhaotong City has a plateau monsoon climate with altitude differences; thus, the temperature changes had a great impact on the growth of vegetation. The areas with a significant negative correlation accounted for 0.72%, mainly distributed in the central Dali Prefecture, central Baoshan City, and the others sporadic distribution in the study area. NDVI was positively correlated with precipitation, indicating the positive effect of precipitation on vegetation growth; the areas with a positive correlation accounted for 62.72%, while 37.28% of the total area exhibited a negative correlation. In this study, the area, where the vegetation NDVI was significantly correlated with precipitation (P< 0.05) accounted for 9.29%, with the area with a significant positive correlation accounting for 7.56%, mainly distributed in Zhaotong City, Qujing City, Kunming City, and Yuxi City in the northwest of the Yunnan Province, having Zhaotong City occupying more areas than the others. Based on the above-mentioned analysis, on the annual scale, the correlation between NDVI and temperature was stronger than with precipitation, indicating the greater importance of the temperature for the growth of vegetation.

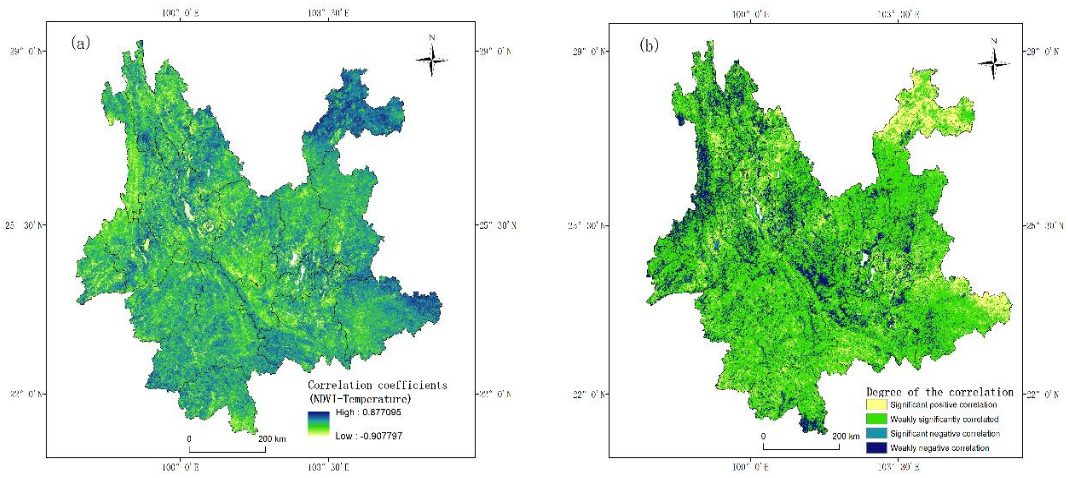

Figure 12. *The correlation coefficient and the degree of the correlation between vegetation NDVI and temperature in Yunnan Province from 2000 to 2020*

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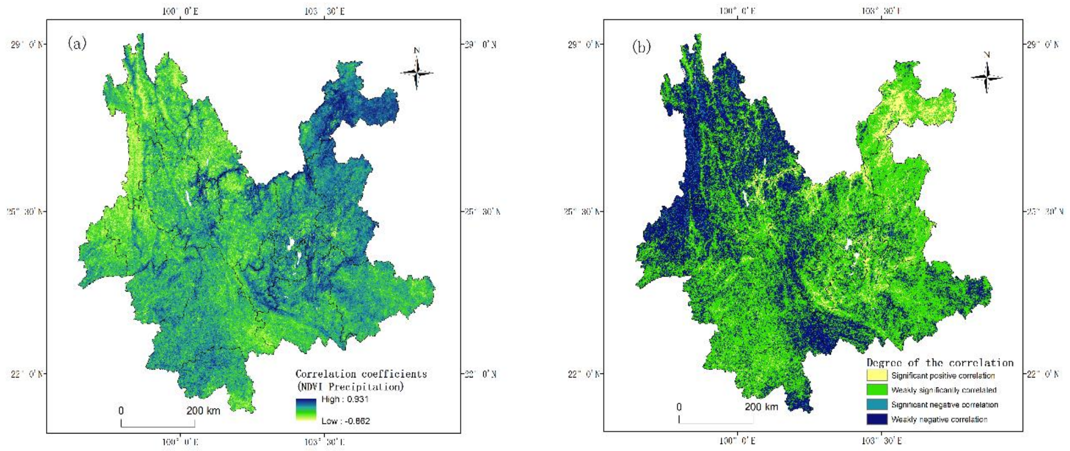

Figure 13. *The correlation coefficient and the degree of the correlation between vegetation NDVI and precipitation in Yunnan Province from 2000 to 2020*

Discussion

Yunnan Province is a plateau and a mountainous area of complex topography encompassing landforms, with the climate change during 2000–2020 (Yu et al., 2020; Sun et al., 2021). The growth status of vegetation is affected by varying degrees of different climatic factors. The vegetation types in Yunnan Province are different. Due to the different types of climates and the differences in altitude, the plants (vegetation) have different growth habits and vary with phenology. In recent years, the average temperature throughout the world has been on the rise due to global warming, which has elicited the response of vegetation to climate change in advance.

In recent years, China has been focusing on the construction of the ecological civilization, improving the vegetation coverage at a rate of 0.09%/a (Xu et al., 2020). This study found the improvement of NDVI with “W” shape on a monthly level. With the high temperature and low precipitation during the spring and summer in Yunnan Province, the growth of vegetation has been inhibited, and the hysteretic nature of precipitation appeared (Liu et al., 2020); this is the reason why NDVI values are low in March and June; these findings are consistent with the results of other studies. At the yearly level, although the vegetation NDVI fluctuated in 2005, 2010, 2012, and 2014, it mainly showed an upward trend in Yunnan Province during the past 21 years. These fluctuations were due to the efforts to protect the ecological environment and biodiversity, monitor large-scale afforestation efforts, and create wetland parks for many years. In Yunnan Province, the first phase of the policy began with returning farmland to forests and grasslands in 2002. The continuous advancement of measures during the past ten years has gradually improved the vegetation NDVI; this is consistent with the findings of previous studies (Liu et al., 2017; Li et al., 2018; Xiong et al., 2018). The spatial distribution and pattern of vegetation NDVI decreased from south-west to northeast in Yunnan Province, due to the low elevation and large vegetation in the southwestern Yunnan (Jian et al., 2019), while the urban construction was not particularly considered in this area. However, in the northeast of Yunnan Province, the urban construction was considered; urbanization is expanding, and the scope of human activities is great. Urban development has led to the rapid reduction of vegetation (Pan, 2016), resulting in the lower vegetation NDVI than in

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the southwestern region. Due to the high altitude in mountains and valleys in northwestern Yunnan, the vegetation NDVI values are relatively low.

Climatic factors are the main factors affecting the vegetation NDVI. This study showed that the temperature increased gradually, and precipitation changes were not significant but with a slight downward trend. Correlation analysis showed that the changes in temperature and vegetation NDVI had a stronger correlation which is consistent with the results of other studies (Liu and Chen, 2018). Yunnan Province has experienced many droughts during the past 21 years, especially during 2009–2012 (Wang et al., 2014; Yu et al., 2020), which resulted in large fluctuations and the decline in NDVI during the past four years. Twenty years is not a long enough time to effectively detect significant trends in precipitation and temperature. In this study, NDVI showed an increasing trend and precipitation showed a decreasing trend; from the perspective of data analysis NDVI and precipitation show a positive correlation, with a positive correlation area of 62.72%, but a significant ($P<0.05$) positive correlation area of 7.56%, This also indicates that probably in some areas of Yunnan Province, the influence of precipitation on NDVI is not significant. The Yunnan Province ranks first in China for its biodiversity, but its ecological environment is still fragile. Moreover, it is particularly important to protect the ecological environment in the protected region.

Conclusion

This study focused on long time series and remote sensing and meteorological data, analyzing the temporal and spatial characteristics, changing trends, future trends, stability, and the response of the vegetation NDVI to climate factors using a variety of analysis methods in Yunnan Province during the past 21 years. The main results are as follows:

(1) During the past 21 years, the NDVI in Yunnan Province increased with "W"-shape, with a growth rate of 0.145/10a. The highest value was found in September, while the lowest was recorded in June. The inter-annual NDVI changes increased significantly with volatility, at the rate of 0.033/10a. The average NDVI in Yunnan Province was 0.614, and the vegetation NDVI decreased from the high-value area of the south-west to the low-value area of the northeast. The monthly and annual NDVI values based on the barycenter migration analysis were stable, mainly in both the south-west and northeast directions.

(2) The vegetation NDVI during the past 21 years showed an increasing trend. The improved area in Yunnan Province accounted for 64.48%, including 48.92% and 15.56% for areas with significant and non-significant improvement, respectively. The stable areas accounted for 29.79%. Moreover, the significant and non-significant degraded areas were 3.04% and 2.69% of the total area, respectively.

(3) The future change of vegetation growth trend in Yunnan Province was mainly anti-sustainable. The areas that continue to degrade in the future accounted for 49.42%, indicating that the vegetation in Yunnan Province may follow a trend of degradation. It is necessary to further protect the ecological environment and formulate corresponding policies to prevent the degradation of vegetation. The coefficient of variation (CV) of vegetation NDVI in Yunnan Province during the past 21 years was 0.018–1.228, with an average value of 0.080, mainly with minor fluctuations. The regions with large fluctuations appeared near plateau lakes, and high-altitude regions were located in Diqing and Nujiang prefectures.

(4) The temperature increased at the rate of 0.928 °C/10a in Yunnan Province during the past 21 years, while the precipitation decreased at a rate of 39.6 mm/10a. Both

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temperature and precipitation decreased gradually from the south-west to the northeast. Partial correlation analysis of two climatic factors and NDVI showed that the area with a positive correlation between temperature and NDVI accounted for 81.06%, whereas the area with a negative correlation accounted for 18.94%. Furthermore, the areas with positive and negative correlations between precipitation and NDVI accounted for 62.72% and 37.28%, respectively. Both climatic factors had a positive effect on plant growth. In general, the study area was more affected by temperature, and the northeast of this study area was mainly affected by precipitation.

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