SPATIAL AND TEMPORAL VARIATIONS OF NDVI AND ITS RESPONSE TO CLIMATIC FACTORS IN THE LIJIANG RIVER BASIN, CHINA, FROM 2000 TO 2022

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Abstract. Understanding how vegetation changes over time and adapts to climate variations is vital for the preservation of ecosystems and ensuring long-term sustainability. However, there is little research on the Lijiang River Basin, particularly regarding seasonal-scale studies. Using MOD13A1 NDVI data (2000-2022), this study examined the NDVI's spatiotemporal changes over the previous 23 years in the Lijiang River Basin, utilizing techniques such as trend analysis, coefficient of variation, and partial correlation. Additionally, it assessed how climate change impacted NDVI. According to the results, the NDVI increased by about 0.2% annually between 2000 and 2022, indicating a positive trend over the Lijiang River Basin. Over 97% of the region exhibited relatively low variability, with areas of significant NDVI increase or decrease concentrated in regions with intensive human activity. Vegetation cover changes were influenced by both human construction and plantation forestry. From 2000 to 2022, the NDVI values indicated high vegetation coverage, with more than 97% of the area displaying medium to high vegetation (NDVI > 0.6). At the inter-annual scale, temperature exhibited a stronger positive correlation with NDVI. Seasonally, the relationship between temperature and NDVI was strongest during spring and summer. In contrast, although temperature and rainfall showed positive correlations with the vegetation index in fall and winter, rainfall exhibited a stronger relationship during these seasons.
Keywords: *vegetation changes, ecosystems, trend analysis, partial correlation, temperature, rainfall*

Introduction

Terrestrial ecosystems depend heavily on vegetation, and human activity and climate change are the primary causes of changes in these ecosystems (Shi et al., 2021). Vegetation dynamics is now a primary focus of global change studies and geographic research because they provide essential insights into ecosystem resilience when examining how vegetations are impacted by human activities and climate change (Gao et al., 2017; Krishnaswamy et al., 2014; Wang et al., 2016). A popular remote sensing method for evaluating plant cover is NDVI, which stands for Normalized Difference Vegetation Index and is widely used in research on ecosystem monitoring and vegetation changes in different regions (De La Iglesia Martinez et al., 2023; Matsushita et al., 2007; Robinson et al., 2017; Tucker, 1979).

Recent studies have utilized NDVI to analyze vegetation dynamics across various regions. For instance, a study conducted in the Yangtze River Basin between 1982 and 2015 showed a substantial overall rise in vegetation cover, with notable spatial variation shaped by climatic influences (Wang et al., 2022). Similarly, research conducted in the Loess Plateau of China has demonstrated that factors such as precipitation, humidity, atmospheric pressure, air temperature, and sunshine duration play a vital part in NDVI variations (Li et al., 2021). These findings highlight the importance of considering multiple factors when assessing vegetation changes. Additionally, numerous studies have examined vegetation changes in various climatic zones, such as arid (Zhu et al., 2019), semi-arid (Fensholt et al.,

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2012), humid (Zhou et al., 2021), and semi-humid (Wang et al., 2020) regions, identifying the factors that influence vegetation changes. Similarly, In the Karst region of southwest China, there have been numerous studies exploring the relationship between NDVI and climate factors (Wu et al., 2023; Xue et al., 2023). However, a gap exists in studies examining variations in vegetation cover across various watersheds and how these ecosystems respond to climate factors (Sun et al., 2023). Furthermore, vegetation's reaction to climate factors differs by season (Feng et al., 2021), with most studies concentrating on annual NDVI trends, leaving seasonal variations and their climatic drivers largely unexplored. Seasonal NDVI dynamics provide crucial insights into vegetation's sensitivity to seasonal climatic variations, including temperature and precipitation, which fluctuate significantly throughout the year (Piao et al., 2011).

Situated in southern China, the Lijiang River Basin is one significant natural region. that is humid and characterized by a delicate environmental balance (Li et al., 2025). Its ecological significance is further highlighted by its status as a globally renowned natural scenic tourist destination. Consequently, monitoring vegetation changes and understanding the vegetation-climate response in this region is essential, as it provides valuable insight into ecological health and informs environmental conservation efforts.

The purpose of this study is to evaluate the Lijiang Basin's NDVI's spatiotemporal dynamics between 2000 and 2022 and to study its correlation with meteorological factors. By integrating annual and quarterly NDVI data with climate data, and applying trend analysis, coefficient of variation, as well as partial correlation methods, we investigated the spatiotemporal patterns of vegetation cover in the Lijiang River Basin. We examined how annual and seasonal climate changes influence vegetation dynamics in the region. In this study, vegetation dynamics are thoroughly investigated, and the seasonal-scale relationship between vegetation and climate factors addresses a gap in the Lijiang River Basin. The results will deliver critical insights for focused vegetation rehabilitation and sustainable ecological management, supporting the long-term recovery and progress of the Lijiang Basin.

Materials and methods

Study area

The Lijiang River Basin, a representative karst landscape area (Shen et al., 2024), is located between 24°38′10″and 25°53′59″N, and 110°07′39″and 110°42′57″E, covering an area of approximately 5585 km^2 (*Fig. 1*). The basin extends north to south and includes several counties and districts, including Xingan County and Lingchuan County. The Lijiang River Basin's climate is characterized by rainy, scorching summers and dry, freezing winters. It is recognized as a national key ecological protection region and a significant water conservation area in the Pearl River Basin (Mao et al., 2014). Given its environmental importance, with the famous Lijiang River scenic area, one national nature reserve, and two autonomous regional nature reserves, studying vegetation changes in the basin is crucial.

Data acquisition

The MODIS NDVI dataset (MOD13A1) spanning from 2000 to 2022 was sourced from https://ladsweb.modaps.eosdis.nasa.gov, the NASA website, and retrieved via Google Earth Engine (GEE). The time resolution of this dataset was 16 days, and its

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spatial resolution was 500 meters. Using the Maximum Value Composite (MVC) approach, the NDVI data for the year and the season were produced.

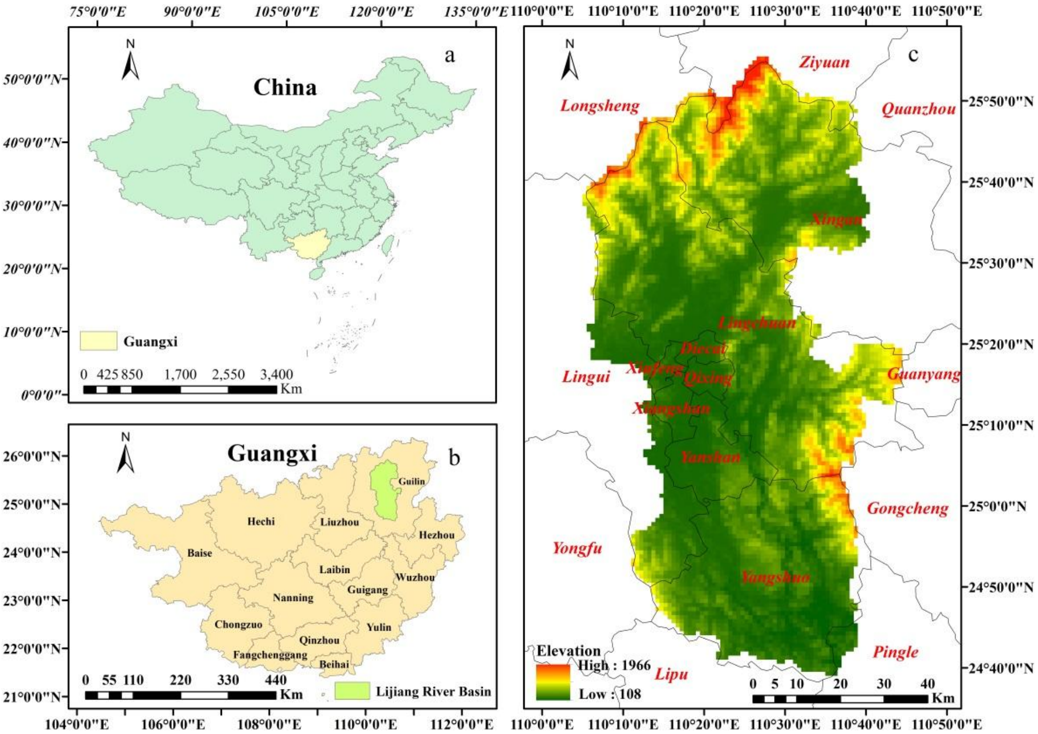

***Figure 1.** Study area. (a) China; (b) Guangxi; (c) Lijiang River Basin*

The National Tibetan Plateau Data Center (TPDC) provided the temperature and precipitation data (https://data.tpdc.ac.cn). The precipitation dataset provides monthly data for China in NETCDF (.nc) format, with a geographical resolution of 0.0083333° (~1 km) and a timeframe of January 1901 to December 2023. The data was generated via the Delta spatial downscaling technique, based on the 0.5° CRU global climate dataset and the high-resolution WorldClim dataset. Verification with data from 496 independent meteorological stations confirms the reliability of the dataset (Peng, 2020). The temperature dataset offers monthly mean temperatures with a resolution of 0.0083333 arc degrees (~1 km) for China, covering the period from January 1901 to December 2023 in NETCDF (.nc) format. The data, with a unit of 0.1°C, was downscaled from CRU TS v 4.02 and WorldClim datasets using the Delta downscaling method. Data from 496 weather stations across China were used to evaluate and confirm the reliability of this dataset for climate change studies (Peng, 2019). The temperature and precipitation data were resampled to match the 500 m resolution of the MOD13A1 NDVI data to conduct spatial analyses.

The NPP-VIIRS-like Global Nighttime Light Dataset (2000–2023) was sourced from Harvard Dataverse (https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/YGIVCD) and developed by researchers at East China Normal University and Fuzhou University. This dataset was constructed using an enhanced auto-encoder model to perform cross-sensor calibration between DMSP-OLS and NPP-VIIRS nighttime light data. By utilizing the Enhanced Using Annual Nighttime Light Index (EANTLI) data from 2000 to 2012 and validating the results against the NPP-VIIRS

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annual composite data for 2013, a consistent nighttime light dataset with a 500-meter spatial resolution was generated by the model. This continuous nighttime light dataset from 2000 to 2023 provides enhanced temporal consistency and the capability to capture socio-economic dynamics across different spatial and temporal scales (Chen et al., 2020).

Methods

Calculation of NDVI trends

In this research, NDVI trends in the Lijiang River basin between 2000 and 2022 were analyzed per pixel using the Theli-Sen slope test (Cao et al., 2014; Qin et al., 2021), with statistical significance determined by the Mann-Kendall test (Song et al., 2020).

$$\theta_{\text{slope}} = \frac{n \times \sum_{i=1}^{n} (i \times NDVI_i) - \left(\sum_{i=1}^{n} i\right)\left(\sum_{i=1}^{n} NDVI_i\right)}{n \times \sum_{i=1}^{n} i^2 - \left(\sum_{i=1}^{n} i\right)^2} \quad \text{(Eq.1)}$$

where n denotes the number of years of study, and *NDVIi* refers to the maximum NDVI in the *ith* year. A positive value (>0) suggests an increase in NDVI over n years, while a declining trend is indicated by a negative value. Trend analysis effectively characterizes the changes in NDVI across different regions of the Lijiang River Basin during the study period, providing a spatial perspective for vegetation protection policy development.

The significance of these NDVI variation trends was assessed using the F-test. The formula is:

$$F = \frac{\sum_{i=1}^{n} \left(\hat{x}_i - \bar{x}\right)}{\sum_{i=1}^{n} \left(x_i - \bar{x}\right) / (n-2)} \sim F(1, n-2) \quad \text{(Eq.2)}$$

where $\hat{x}_i$ refers to the regression value, $\bar{x}$ denotes the mean of the NDVI data, and n represents the duration of the study period. A p-value of 0.05 or less indicates that a trend is significant. The F-test effectively evaluates the significance of NDVI trend variations across different regions of the Lijiang River Basin.

Stability analysis

A standard tool for assessing the stability and volatility of time series data is the coefficient of variation *(Cv)*, which is the standard deviation to mean ratio (Alharbi et al., 2019). This study calculates the *Cv* for NDVI at the pixel level to assess temporal stability, applying the formula below:

$$C_v = \frac{1}{\bar{x}} \sqrt{\frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n-1}} \quad \text{(Eq.3)}$$

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where C_v signifies the coefficient of variation of the NDVI values, n represents the period of years, x_i indicates the pixel value for year i, and $\bar{x}$ represents the mean NDVI value for the pixel from 2000 to 2022. A higher C_v value indicates greater data dispersion and more significant inter-annual NDVI variation, while a lower value suggests a tighter data distribution and more consistent NDVI variation over the years.

Partial correlation analysis model

This basic correlation coefficient yields a partial correlation coefficient. It measures the correlation between temperature or precipitation and NDVI, which is described as follows:

$$r_{xy,z} = \frac{r_{xy} - r_{xz}r_{yz}}{\sqrt{(1-{r_{xz}}^2)(1-{r_{yz}}^2)}} \tag{Eq.4}$$

Hence, with z held constant, Variables x and y have a partial correlation coefficient of $r_{xy,z}$. Additionally, the simple correlation coefficients among the three variables x, y, and z are denoted by the symbols r_{xy}, r_{xz}, and r_{yz}, respectively (Ning et al., 2015). Partial correlation analysis can more accurately identify the independent relationships between NDVI, temperature, and precipitation in the Lijiang River Basin.

Results

Characteristics of NDVI's spatiotemporal variations

Characteristics of the Lijiang River Basin's annual NDVI temporal variation

This is a synopsis of the inter-annual NDVI change in the Lijiang River Basin, as seen in *Figure 2*: (1) With an annual increase rate of roughly 0.19%, the Lijiang River Basin's annual NDVI showed a notable rising trend between 2000 and 2022, with a spatial mean ranging from 0.7905 to 0.8343. (2) Throughout the 23 years, the highest annual NDVI occurred in 2021, while the lowest was recorded in 2003, with the maximum value being approximately 5.54% higher than the minimum. (3) In 2011, the Guangxi government introduced the "Rules for the Lijiang River Basin's Ecological Environmental Protection," which established legal responsibilities for ecological protection and prohibited illegal activities such as quarrying, sand dredging, and waste disposal along the riverbanks. Consequently, the yearly NDVI variations over the 23 years can be divided into two phases: 2000-2011 and 2011-2022. The overall trend reveals that the 2000-2011 period marked significant, stable growth, with a growth rate of approximately 0.33%, which is 6.6 times greater than the rate of growth between 2011 and 2022.

Spatial distribution of NDVI

To better understand the spatial distribution of NDVI in the Lijiang River Basin, twenty-three NDVI images were area-averaged to produce the NDVI-averaged images for 23 years (*Fig. 3*). Using ArcGIS's equal interval approach, the NDVI readings were categorized into five categories (Zhang et al., 2022; Zhu et al., 2021). Specifically, the categories of high vegetation, medium-high vegetation, medium vegetation, medium-low vegetation, and low vegetation correspond to the ranges of 0.8-1.0, 0.6-0.8, 0.4-0.6, 0.2-0.4 and 0-0.2, respectively (*Table 1*).

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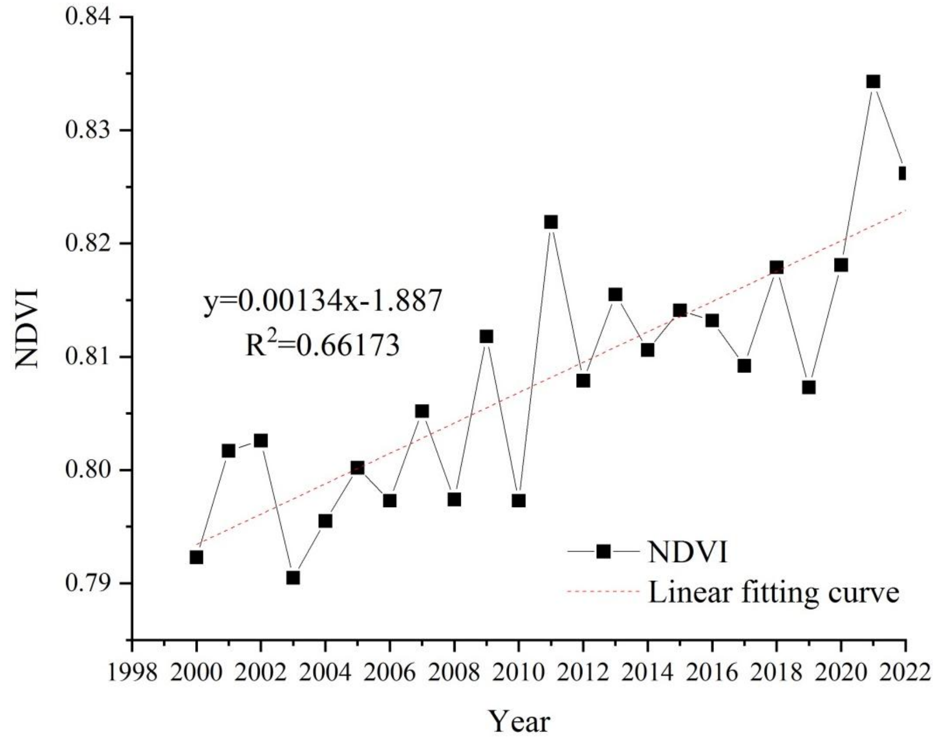

Figure 2. *Temporal change trend of the spatial mean of the NDVI between 2000 and 2022*

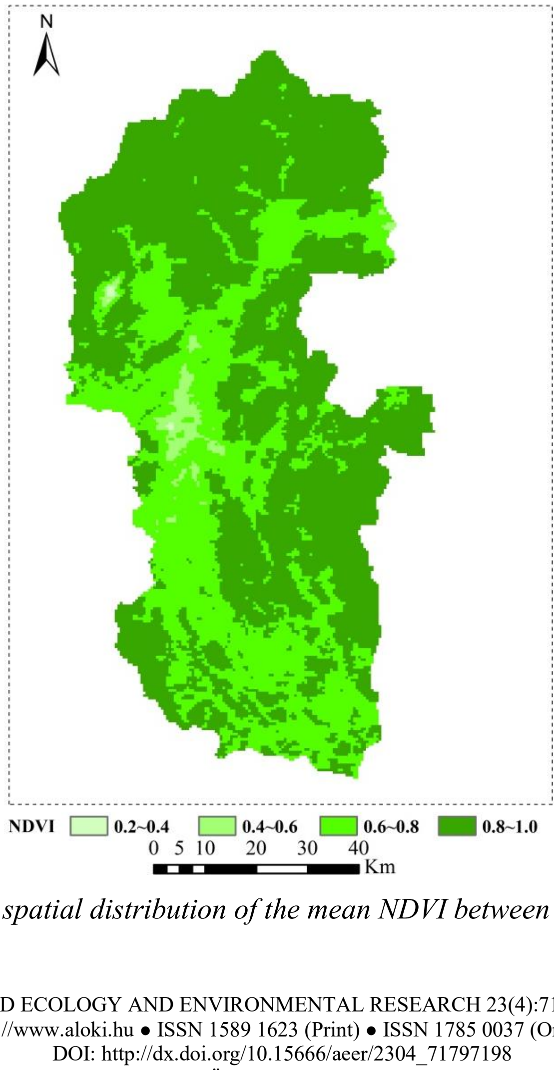

Figure 3. *The spatial distribution of the mean NDVI between 2000 and 2022*

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Table 1. *The proportions of different grades of NDVI*

NDVI	Counts	Proportions	Grades
0~0.2	0	0	Low vegetation
0.2~0.4	20	0.08%	Medium-low vegetation
0.4~0.6	447	1.73%	Medium vegetation
0.6~0.8	9041	34.90%	Medium-high vegetation
0.8~1.0	16400	63.30%	High vegetation

As shown in *Figure 3* and *Table 1*: (1) The Lijiang River Basin has a comparatively high NDVI. Most northern, eastern, and southwestern regions exhibit medium-high to high vegetation. The biological features of the Lijiang River Basin as a nature reserve are reflected in the proportion of high vegetation, which is 63.14%, and the overall percentage of medium-high and above vegetation, which exceeds 97%. (2) The vegetation level in areas with human activity, such as Guilin City in the central part of the basin, is slightly lower, which is closely related to the urbanization process.

Characteristics of spatial variation of NDVI

(1) NDVI trend and significance testing

To better explore variations in vegetation in the study area, trends in the 23-year NDVI were examined. Using pixel-by-pixel analysis with the Theil-Sen slope methods and the Mann-Kendall significance test (*Fig. 4*), five categories were then created from the results (*Tables 2* and *3*).

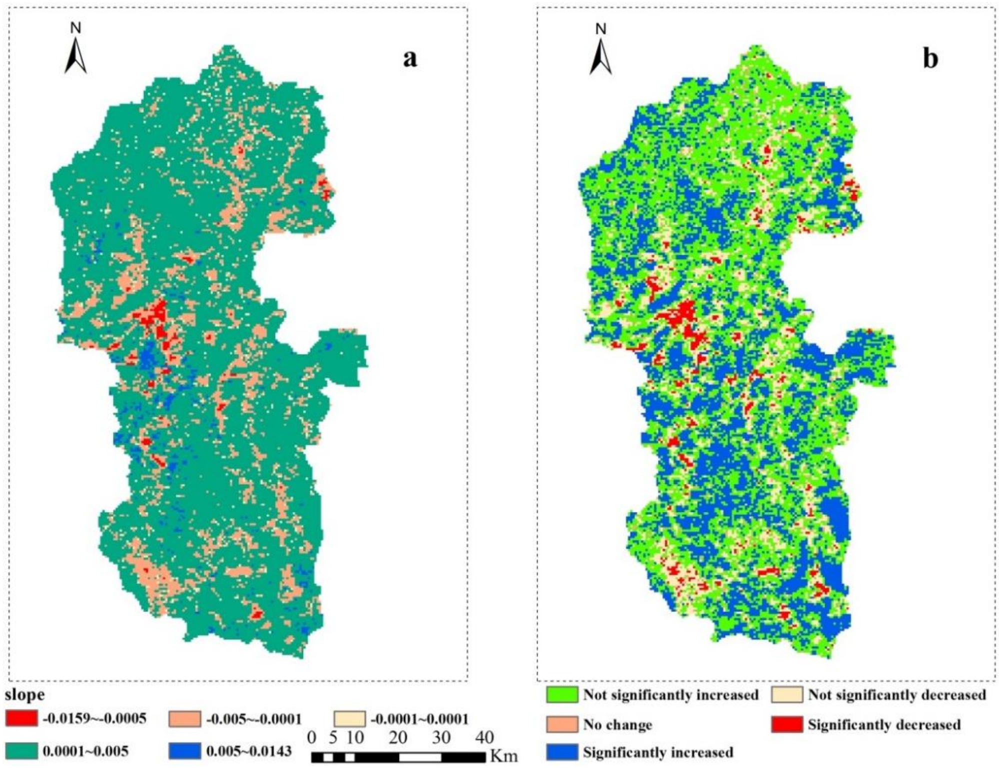

Figure 4. *The Lijiang River Basin's NDVI trend and significance testing between 2000 and 2022. (a) θslope; (b) θslope & significance testing*

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Table 2. *Proportion of grades with different slope ranges*

Slope range	Counts	Proportions
0.005~0.0143	495	1.91%
0.0001~-0.005	20217	78.03%
-0.0001~0.0001	694	2.68%
-0.0005~-0.0001	4247	16.39%
-0.159~-0.0005	255	0.98%

Table 3. *Proportion of grades with different slope & significance*

θ_{slope} & significance	Counts	Proportions	Category
$\theta_{slope} > 0.0001$, $p \leq 0.05$	8579	33.11%	Significantly increased
$\theta_{slope} > 0.0001$, $p > 0.05$	12133	46.93%	Not significantly increased
$-0.0001 < \theta_{slope} \leq 0.0001$	694	2.68%	No change
$\theta_{slope} \leq -0.0001$, $p > 0.05$	789	3.05%	Not significantly decreased
$\theta_{slope} \leq -0.0001$, $p \leq 0.05$	3713	14.33%	Significantly decreased

According to *Equation 1*, pixel-by-pixel analysis of NDVI was performed to ascertain the NDVI change during the previous 23 years. The statistics (*Table 2*) in *Figure 4a* show that the slope values ranged from -0.01587 to 0.01433, with 79.68% of the entire region indicating an increasing NDVI trend ($\theta_{slope} > 0$). This suggests that plant cover in the study area has risen, and the ecological structure has improved annually from 2000 to 2022. However, a declining tendency was observed in 20.32% of the research area, mostly in the central region, including Yangshuo County in the south and the Guilin urban area.

The significance test of the θ_{slope} was performed, and the distribution of NDVI trends with significant results was obtained (*Fig. 4b*). Of the regions tested, 36.16% passed the significance test ($p \leq 0.05$), while 63.48% did not ($p > 0.05$). The trend results were superimposed on the significance results, as follows: (1) significant increase ($\theta_{slope} > 0.0001$, $p \leq 0.05$), (2) non-significant increase ($\theta_{slope} > 0.0001$, $p > 0.05$), (3) no change ($-0.0001 < \theta_{slope} \leq 0.0001$) (4) non-significant decrease ($\theta_{slope} \leq -0.0001$, $p > 0.05$), (5) significant decrease ($\theta_{slope} \leq -0.0001$, $p \leq 0.05$). The results indicated that 8579 pixels exhibited a significant increase, accounting for 33.11%, while 12,133 pixels showed a non-significant increase, accounting for 46.93%. Additionally, 694 pixels exhibited no change, accounting for 2.68%; 789 pixels showed a non-significant decrease, accounting for 3.05%, and 3713 pixels exhibited a significant decline, accounting for 14.33%. Notably, regions with substantial increases were spread across the area, while the considerable decrease was primarily concentrated in the urban area of Guilin.

(2) Spatial variation of different NDVI grades

To further analyze the year-to-year variations in the NDVI class distribution within the study area, hierarchical mapping was conducted every two years starting from 2000, resulting in a total of 12 categorized maps for the period from 2000 to 2022. As shown in *Figure 5*, the regions with medium and high vegetation expanded significantly, particularly in the northern region of the Lijiang River Basin. The high vegetation generally showed a continuum of characteristics, going from patchy to more uniform covering.

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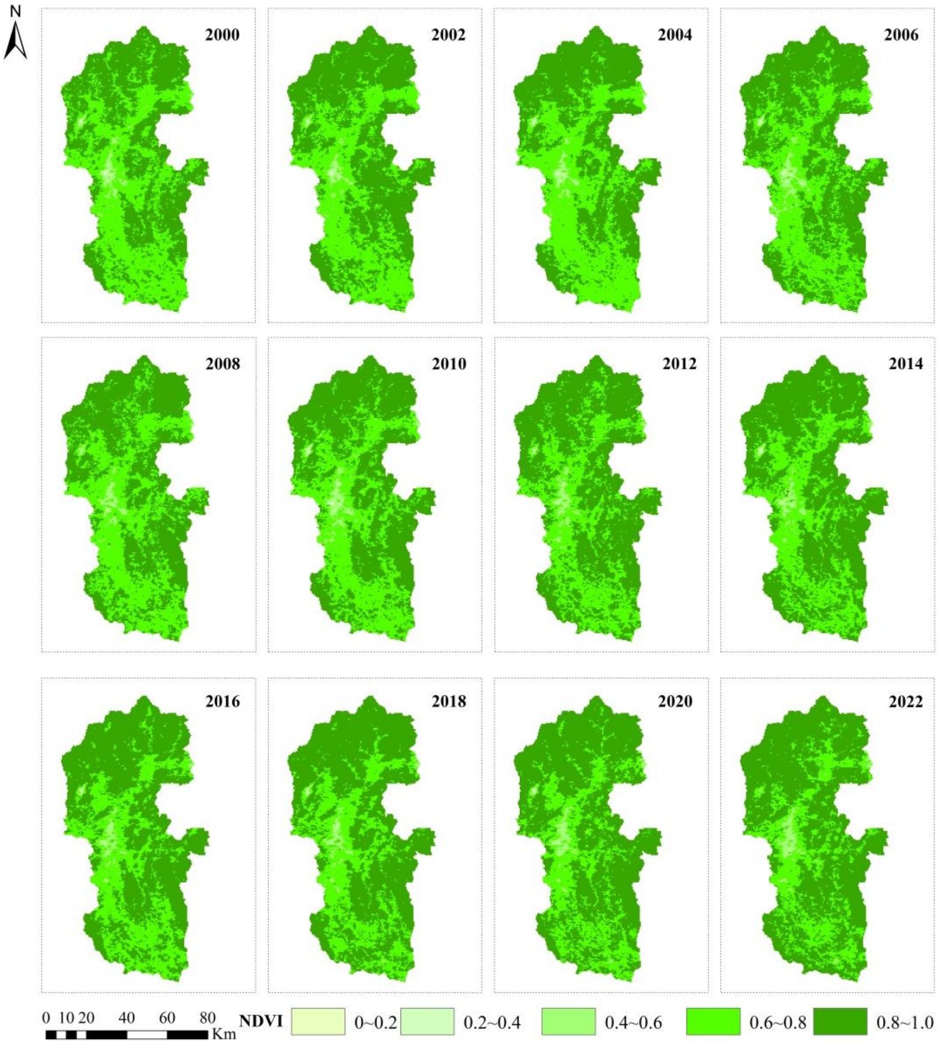

Figure 5. *The spatial distributions of NDVI from 2000 to 2022*

At the same time, the changes in the proportions of different vegetation grades were analyzed (*Fig. 6*), revealing the following findings: (1) From 2000 to 2022, over 97% of the entire research region was covered by medium-high and high vegetation, while the proportion of sparse and no vegetation was no more than 3%, showing a significant improvement in vegetation condition in the study area. (2) From 52% in 2000 to 70% in 2022, the high vegetation portion of the Lijiang River Basin rose dramatically, representing an 18% increase. (3) Between 2000 and 2022, the percentage of medium-to-high vegetation dropped by 19%, from 46% in 2000 to 27% in 2022. These trends indicate that medium-high vegetation in the Lijiang River Basin gradually transitioned to high vegetation throughout the study period, further demonstrating the ongoing improvement of the ecological environment driven by restoration efforts.

Stability analysis

According to *Equation 3*, variability analysis of the inter-annual NDVI values of each pixel between 2000 and 2022 revealed the fluctuating changes in NDVI across the study area (*Fig. 7a*). Based on related studies (Liu et al., 2016), based on its magnitude, the *Cv*

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was divided into five classes.: high volatility ($Cv \geq 0.2$), relatively high volatility ($0.15 < Cv \leq 0.2$), medium volatility ($0.1 < Cv \leq 0.15$), relatively low volatility ($0.05 < Cv \leq 0.1$), and low volatility ($Cv \leq 0.05$).

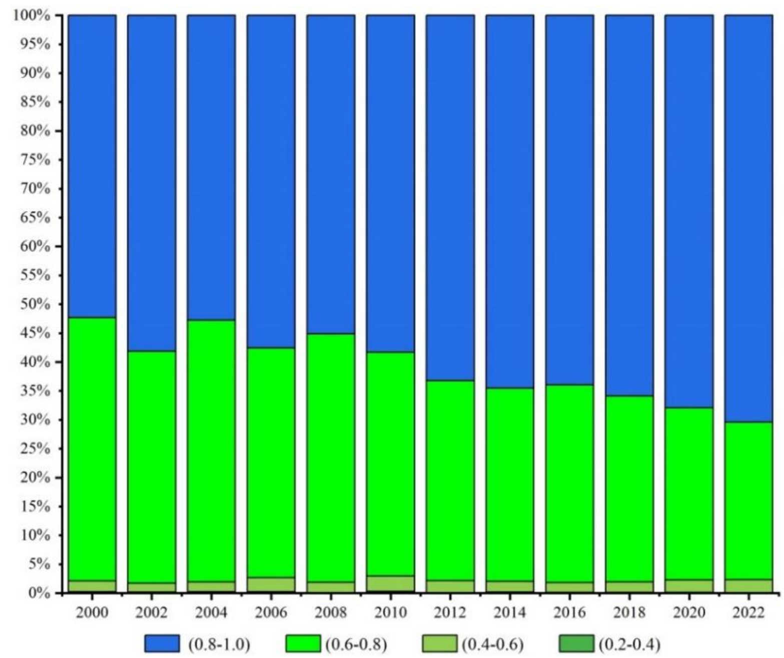

Figure 6. *The change in the proportion of NDVI for different grades from 2000 to 2022*

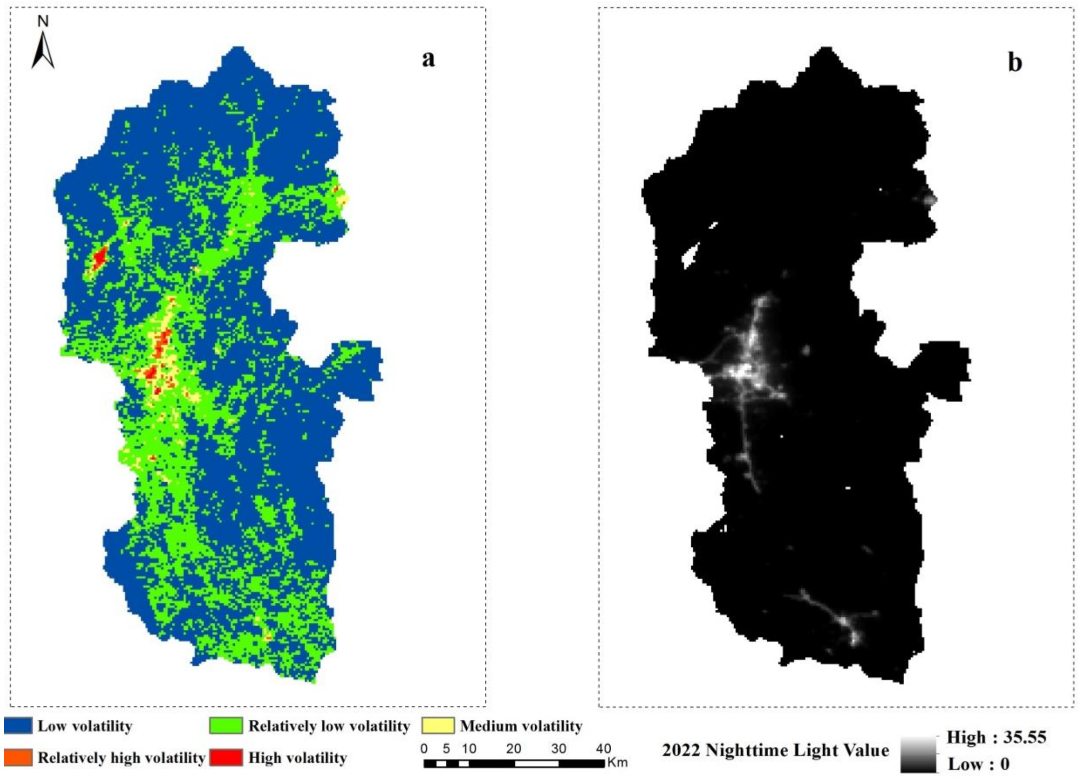

Figure 7. *The NDVI coefficient of variation's spatial distribution from 2000 to 2022 (a) and Nighttime Light distribution in 2022 (b)*

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From *Figure 7a* and *Table 4*, it is evident that the volatility in most areas of the Lijiang River Basin was small, with low volatility areas making up about 67% of the all, accounting for the largest proportion, primarily found in the upper Lijiang River Basin and southeastern areas, and relatively low volatility accounting for about 30%, primarily centered on the Lijiang River Basin's central area. The proportion of medium and above volatility is relatively low, less than 3%, and its spatial distribution is mainly concentrated in the main civic regions of Guilin city and counties, where human activities are intensive, with significant spatial overlap with the high nighttime light areas (*Fig. 7b*), reflecting the significant human activity's effect on variations in the NDVI.

Table 4. *Classification of the NDVI coefficient of variation*

C_v	Counts	Proportions	Classes
≤ 0.05	17472	67.32%	Low volatility
0.05~0.1	7805	30.07%	Relatively low volatility
0.1~0.15	512	1.97%	Medium volatility
0.15~0.2	116	0.45%5	Relatively high volatility
＞0.2	50	0.19	High volatility

Response of NDVI to climate factors in the Lijiang River Basin

To further examine the spatial variations in the impacts of precipitation and temperature on NDVI in the study area, partial correlation analyses, and significance tests were conducted on NDVI concerning both temperature and precipitation data. Additionally, temperature, precipitation, and NDVI data at the season scale were analyzed to better understand vegetation's response to climate change over shorter time scales. These seasonal datasets were then given the same partial correlation analysis.

Response of annual NDVI to climatic factors

The partial correlation results were statistically analyzed using ENVI, which produced average correlation coefficients of -0.0241 and 0.1727 between NDVI and annual cumulative precipitation and between NDVI and annual mean temperature, respectively. Overall, these results suggest that the correlation between NDVI and temperature was stronger across the Lijiang River Basin.

The percentage of areas exhibiting a positive correlation between NDVI and temperature was 75.22%, of which 9.31% had correlation coefficients greater than 0.5 (*Table 5*), indicating a strong positive correlation, primarily across the eastern and northern regions of the study region (*Fig. 8a*), though relatively dispersed. The percentage of areas with correlation coefficients less than -0.5, indicating a strong negative correlation, was 1.48% (*Table 5*), mainly in the Guilin metropolitan areas and the southern portion of the study region. Additionally, Results were significant in 20.69% of the locations ($p \leq 0.05$) (*Table 6*). This includes all areas with strong positive and negative correlations, confirming their statistical significance. The correlation results were then combined with the significance test results, as shown in *Figure 8b*.

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Just 0.78% of the areas had a correlation coefficient larger than 0.5, but 44.79% of the locations had a positive connection between NDVI and precipitation (*Table 7*), indicating a strong positive correlation. These areas, which passed the significance test ($p \leq 0.05$), were sporadically appropriated in the center of the Lijiang River Basin. Additionally, just 0.76% of areas had a correlation coefficient smaller than -0.5, indicating a strong negative link (*Table 7*). These areas, which were also statistically significant ($p \leq 0.05$), were dispersed across various parts of the Lijiang River Basin. The proportion of areas with statistically significant results ($p \leq 0.05$) was only 4.54% (*Table 8*), and this includes all areas with strong positive and negative correlations. The correlation results were then combined with the significance test outcomes, as shown below (*Fig. 9*, *Table 8*).

Table 5. *Graduated statistical table of correlation coefficients between NDVI and temperature*

r	Counts	Proportions
＞0.5	2412	9.31%
0.2~0.5	10792	41.66%
-02~0.2	10119	39.06%
-0.5~-0.2	2202	8.5%
≤ -0.5	383	1.48%

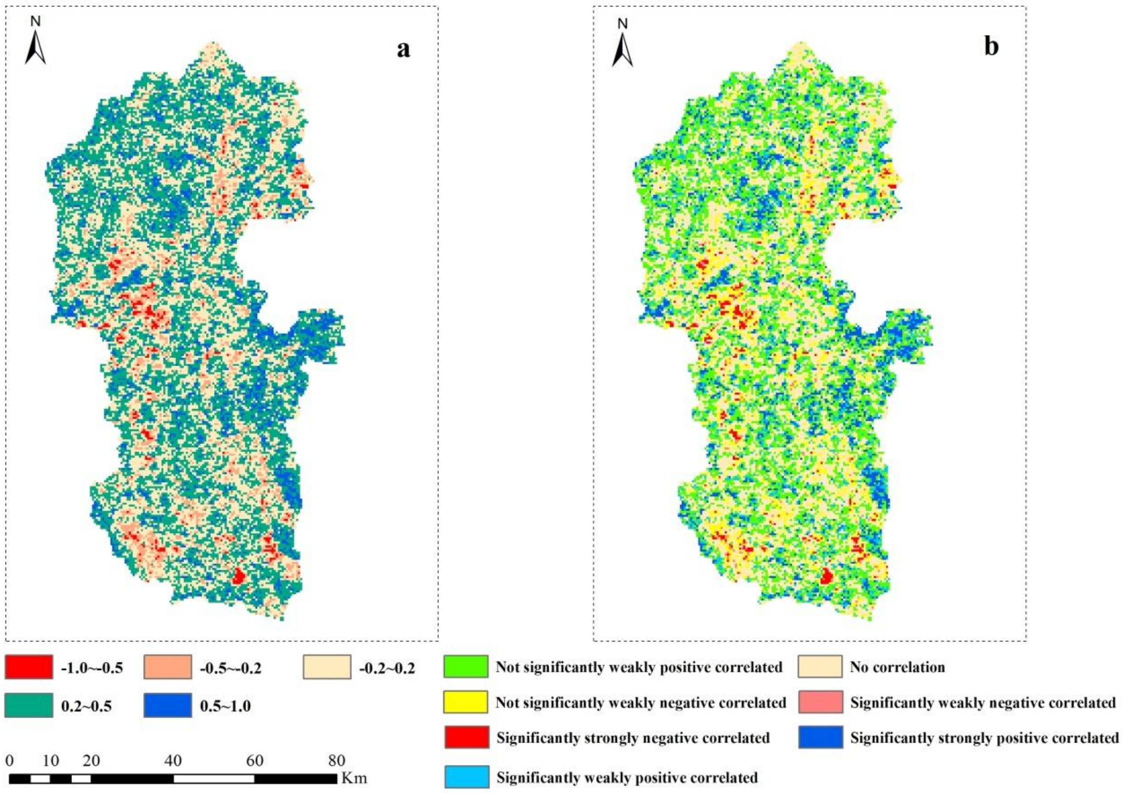

Figure 8. *Spatial distribution of correlation between annual NDVI and temperature. (a) correlation coefficient; (b) correlation coefficient & significance test*

Table 6. *Graduated statistical table of correlation coefficients & significance between NDVI and temperature*

r & significance	Counts	Proportions	Category
0.2~0.5 & p＞0.05	8511	32.85%	Not significantly weakly positively correlated
-02~0.2	10119	39.06%	No correlation
-0.5~-0.2 & p＞0.05	1917	7.4%	Not significantly weakly negatively correlated
≤-0.5, p≤0.05	383	1.48%	Significantly strongly negative correlated
-0.5~-0.2 & p≤0.05	285	1.1%	Significantly weakly negatively correlated
0.2~0.5 & p≤0.05	2281	8.8%	Significantly weakly positively correlated
＞0.5 & p≤0.05	2412	9.31%	Significantly strongly positively correlated

Table 7. *Graduated statistical table of correlation coefficients between NDVI and precipitation*

r	Counts	Proportions
＞0.5	203	0.78%
0.2~0.5	3748	14.47%
-02~0.2	16344	63.08%
-0.5~-0.2	5416	20.9%
≤-0.5	197	0.76%

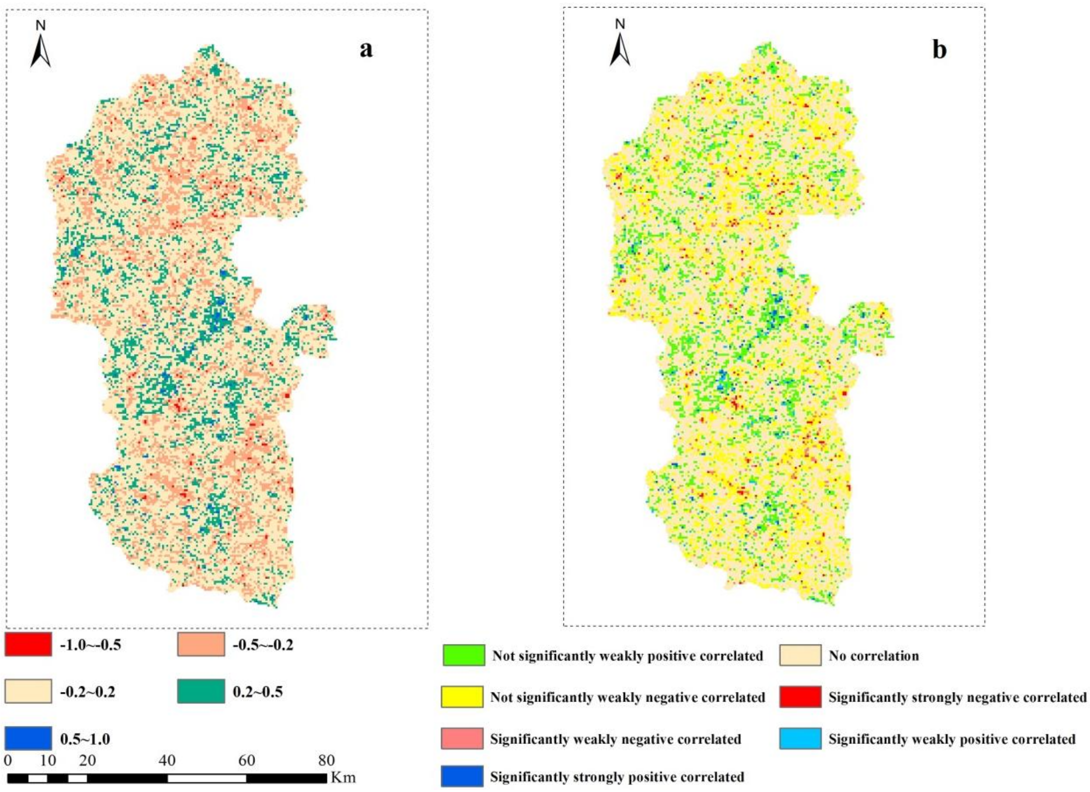

Figure 9. *Spatial distribution of the correlation between annual NDVI and precipitation. (a) correlation coefficient; (b) correlation coefficient & significance test*

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Table 8. *Graduated statistical table of correlation coefficients & significance between NDVI and precipitation*

***r* & significance**	**Counts**	**Proportions**	**Category**
0.2~0.5& p > 0.05	3451	13.32%	Not significantly weakly positively correlated
-02~0.2	16344	63.08%	No correlation
-0.5~-0.2 & p > 0.05	4936	19.05%	Not significantly weakly negatively correlated
≤ -0.5, p ≤ 0.05	197	0.76%	Significantly strongly negative correlated
-0.5~-0.2 & p ≤ 0.05	480	1.85%	Significantly weakly negatively correlated
0.2~0.5& p ≤ 0.05	297	1.15%	Significantly weakly positively correlated
＞0.5 & p ≤ 0.05	203	0.78%	Significantly strongly positively correlated

Seasonal NDVI's reaction to climate variables

To further investigate the reactions of seasonal NDVI to climate factors, this study extracted the maximum NDVI values for the four seasons—spring, summer, autumn, and winter—from 2000 to 2022. Partial correlation analyses were performed pixel-by-pixel, comparing NDVI with corresponding cumulative precipitation and mean temperature. The results of these analyses are presented in *Figures 10* and *11*. It should be noted that the seasons were defined as spring (March to May), summer (June to August), autumn (September to November), and winter (December to February of the following year).

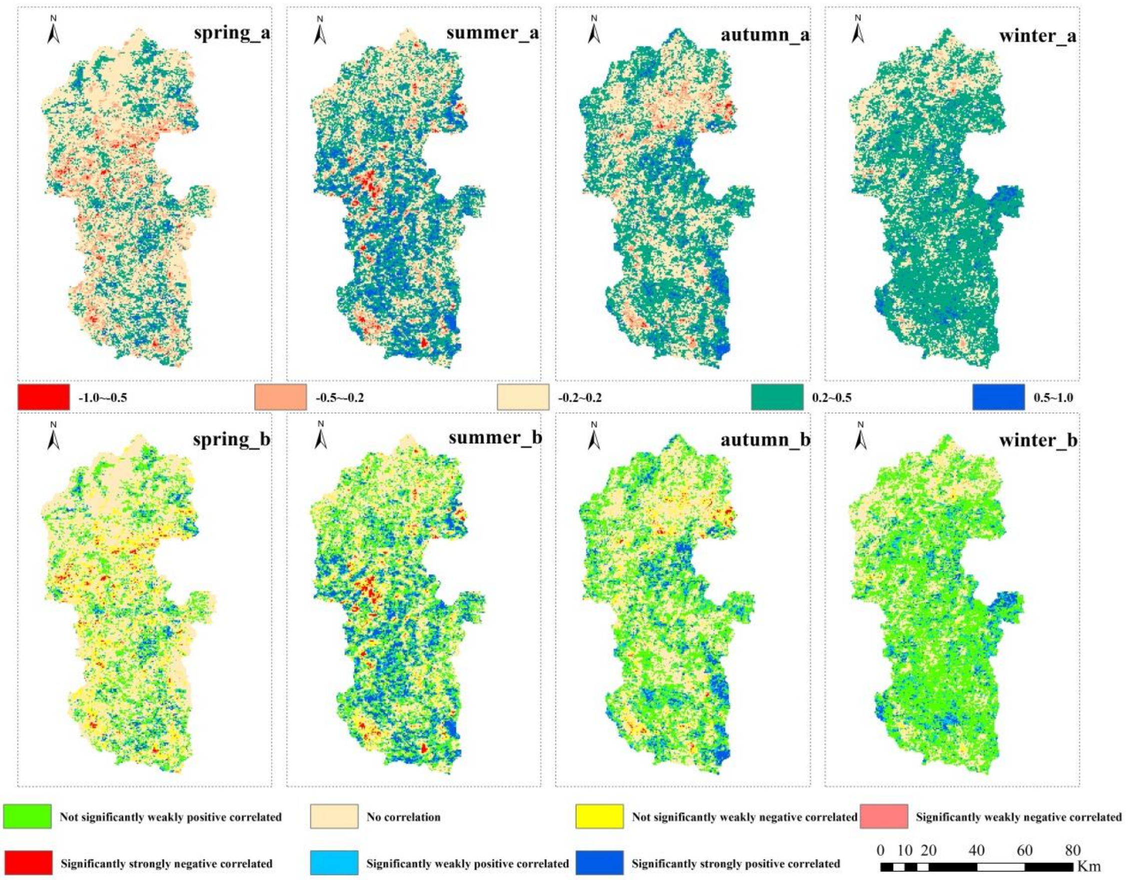

Figure 10. *Spatial distribution of correlation between seasonal NDVI and temperature. (a) correlation coefficient; (b) correlation coefficient & significance test*

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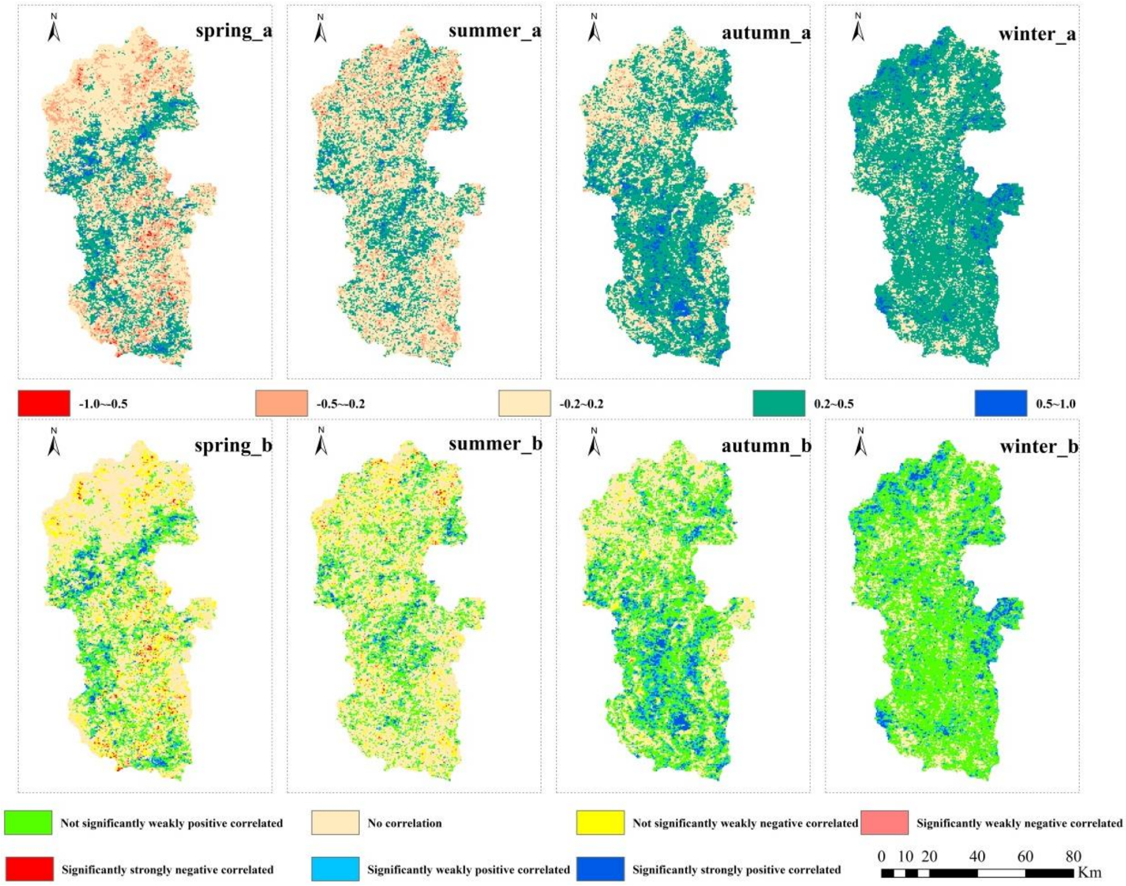

Figure 11. *Spatial distribution of correlation between seasonal NDVI and precipitation. (a) correlation coefficient; (b) correlation coefficient & significance test*

Table 9 illustrates how the relationship between NDVI, temperature, and precipitation varied with the season in the study area. A stronger correlation was observed between NDVI and temperature compared to that between NDVI and precipitation during the spring and summer. In contrast, there was a higher association between precipitation and NDVI in the fall and winter than there was with temperature. The correlation between NDVI in spring and precipitation and temperature is weak, almost negligible. In summer, the correlation between NDVI and precipitation was also comparatively weak, whereas NDVI exhibits a stronger relationship with temperature. There is a comparatively stronger positive link between the NDVI and temperature and precipitation in the fall and winter.

Table 9. *Correlation of NDVI with temperature and precipitation across spring, summer, fall, and winter seasons*

Season	Mean values of NDVI and temperature correlation	Mean values of NDVI and precipitation correlation
Spring	0.0669	0.0531
Summer	0.2070	0.0820
Autumn	0.1919	0.2372
Winter	0.2619	0.3041

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Discussion

Characteristics of spatial variation of NDVI

There was a noticeable increase in the Lijiang River Basin's yearly NDVI between 2000 and 2022, suggesting that the area's ecological quality had generally improved. These results align with research conducted by Wei et al. (2021, 2024) in the Lijiang River basin. Spatially, the regions with growing annual NDVI were primarily situated in Xiangshan District, Xiufeng District, Yanshan District, as well as Qixing District of Guilin City. In contrast, areas with decreasing NDVI were mainly found in DieCai District, Qixing District, and Lingchuan County. Notably, some districts in Guilin, such as Qixing District, exhibited both areas of significant NDVI growth and decline. These areas are concentrated around the central urban zone, where both urban development and artificial afforestation efforts likely contributed to these changes. In other words, urbanization has led to the encroachment on vegetated areas, causing a significant decline in NDVI. However, due to increased focus on the urban environment, artificial afforestation and grass planting have contributed to a notable increase in NDVI within urban areas. In contrast, under the influence of ecological protection policies, natural areas with minimal human disturbance generally showed a slight increase in NDVI, reflecting the natural growth trends in the absence of human interference.

Around 67% of the Lijiang River Basin is made up of low-fluctuation zones, which show a low fluctuation coefficient in terms of NDVI volatility. These regions are mostly found in the basin's northern and southeast parts, as well as other natural regions. Areas with medium and high fluctuations represent a relatively small proportion, less than 10%. The medium and high fluctuation zones show some spatial continuity, mainly in the central urban areas of Guilin and parts of Lingchuan County adjacent to Diecai District, as well as the central urban area of Lingchuan County. These areas are characterized by more frequent human activities and greater human intervention.

The Lijiang River Basin's overall ecological condition is outstanding, as evidenced by the proportion of medium to high vegetation regions exceeding 97%, as determined by vegetation categorization. 63.14% of the basin's whole region was made up of high-vegetation areas, which are primarily found in the basin's north and southeast and spatially overlap with the low-fluctuation zones. Locations with little vegetation were mostly located in locations with a high level of human activity, such as Guilin's center city and the principal cities in the neighboring counties.

Response of NDVI to climate factors

From the partial correlation analysis of annual NDVI with annual mean temperature and cumulative annual precipitation, the NDVI and annual mean temperature and annual cumulative precipitation had average correlation values of 0.1727 and -0.0241, respectively. NDVI in the Lijiang River Basin exhibited a stronger response to temperature, showing a weak positive correlation, while its correlation with precipitation was very weak and negative. Given that the Lijiang River Basin is situated in the subtropical monsoon climate zone, where water and heat conditions are generally sufficient on the inter-annual scale, the average temperature per year is around 18°C. Under the influence of monsoon winds, the region experiences rainfall in spring and summer, while fall and winter are typically dry. The basin's vegetation is primarily subtropical evergreen broad-leaved woods, while there are also shrubs, meadows, and artificial vegetation. On the inter-annual scale, annual cumulative precipitation in the Lijiang River Basin ranges from 1298 mm to

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2258 mm. When precipitation exceeds a certain threshold, the NDVI response shows diminishing or even inverse effects, meaning that as precipitation continues to increase, NDVI does not necessarily exhibit a corresponding growth trend. While rainfall is generally beneficial, excessive rainfall disrupts plant growth by altering growth seasons and affecting soil moisture (Huo et al., 2021; Zeppel et al., 2014).

The partial correlation analysis between seasonal NDVI and seasonal mean temperature and cumulative seasonal precipitation revealed that, during the spring and summer seasons, the partial correlation between NDVI and temperature was relatively high. As a result of the monsoon's impact, the rainy season in the Lijiang River Basin is concentrated in the spring and summer, with abundant rainfall that positively affects vegetation, reaching a marginal effect. In contrast, during the fall and winter seasons, the partial correlation between NDVI and precipitation was higher than that between NDVI and temperature. However, temperature, precipitation, and NDVI all exhibited weak or weak positive correlations. The influence of the monsoon and the change in the angle of direct sunlight during fall and winter led to drought conditions with relatively low temperatures. This combined stress from both water and heat conditions hindered vegetation growth, with water stress being the dominant factor.

Innovation and shortcomings

By adjusting for the impact of additional variables, partial correlation analysis provides a more comprehensive understanding of the actual, independent relationship between two variables. In this study, partial correlation analysis was employed to examine the relationship between NDVI and temperature and precipitation in the Lijiang River Basin. This approach provides a more accurate assessment of vegetation's climate response, offering valuable insights for informed decision-making regarding vegetation protection and sustainable development.

Furthermore, the NDVI's reaction to climate variables is a complicated process, and most previous studies have concentrated on the inter-annual climate response of NDVI, often overlooking its response at shorter time scales, such as the seasonal scale. The Lijiang River Basin, located in the subtropical monsoon climate zone, experiences distinct seasonal changes—spring, summer, fall, and winter—and is influenced by the monsoon, with dry conditions in fall and winter and rainfall in spring and summer. Investigating the climate response of NDVI at the seasonal scale is crucial for understanding the vegetation's climate response characteristics in the basin and forms the foundation for decision-making on vegetation restoration strategies.

However, this study has certain drawbacks. It only examines the partial correlation between temperature, precipitation, and NDVI at specific time points, without exploring the potential delayed effects of precipitation and temperature on vegetation cover. Furthermore, a longer time frame was not used for the analysis and the variations in NDVI in the Lijiang River Basin over an extended time were not evaluated due to the limitations of the available time series data. Additionally, a more thorough analysis of how human activity affects NDVI was left out.

Conclusions

(1) The NDVI in the study area exhibited an upward trend from 2000 to 2022, with a notably higher annual growth rate between 2000 and 2011, approximately 6.6 times greater than the rate observed from 2011 to 2022.

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(2) From 2000 to 2022, most areas of the Lijiang River Basin exhibited minimal NDVI fluctuations, indicating the stability of vegetation changes in the region. Areas with significant NDVI increases and decreases were primarily concentrated in the urban area of Guilin, likely resulting from a combination of afforestation efforts and urbanization. In contrast, under the influence of conservation policies, natural areas generally displayed a slow growth trend.

(3) From 2000 to 2022, the overall NDVI in the Lijiang River Basin indicated high vegetation coverage, with over 97% of the area classified as medium-high or above (NDVI > 0.6). Over time, the proportion of medium and medium-low vegetation showed little change, while the share of medium-high vegetation gradually shifted to high vegetation, reflecting an overall positive trend in vegetation in the region.

(4) The relationship between temperature and NDVI was comparatively strong and positive on an interannual scale in the Lijiang River Basin between 2000 and 2022. On a seasonal basis, spring and summer saw a higher link between temperature and NDVI. In the fall and winter, there was a higher correlation between precipitation and NDVI than between temperature and NDVI, even though both were positively associated. This indicates the differences in the relationship between NDVI and temperature/precipitation on both interannual and seasonal scales, providing valuable insights for vegetation and ecological conservation in the Lijiang River Basin.

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