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Original Research

NDVI-based Vegetation Change and Its Response to Hydrothermal Changes in the Yunnan-Guizhou Plateau of Chinese Karst Regions from 1982 to 2019

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Abstract

This study explored vegetation growth dynamics and their response to hydrothermal changes in the Yunnan-Guizhou Plateau, using GIMMS and MODIS NDVI datasets. The findings reveal: (1) From 2001 to 2019, the MODIS NDVI growth rate (0.0040/a) exceeded the GIMMS NDVI rate (0.0009/a) from 1982 to 2015. (2) The years 1995, 2013, and 1998 are inflection points for GIMMS NDVI, MODIS NDVI, and the annual average temperature, respectively, marking shifts from negative to positive anomalies. (3) Specifically, 56.88% of the area exhibits a significant upward trend for GIMMS NDVI, 69.18% for MODIS NDVI, and 92.5% for the average annual temperature. However, the rainfall trends are inconclusive. (4) Both NDVI datasets show a strong positive correlation with temperature. However, the correlation of MODIS NDVI with temperature was weaker than that of GIMMS NDVI. (5) Broadleaf forests (BDF), coniferous forests (NDF), and tropical monsoon rainforests (TMF) exhibited a significant positive correlation with temperature across both NDVI datasets. In contrast, farmland (FL), grassland (GL), and shrublands(SHR) exhibit varying relationships with temperature. This study enhances our understanding of the interaction between vegetation and climate change on the Yunnan-Guizhou Plateau, providing insights into regional ecological conservation.

Keywords: spectral dataset, vegetation change, hydrothermal characteristics, Yunnan-Guizhou Plateau, karst

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Introduction

The Yunnan-Guizhou Plateau plays a vital role in protecting river basins such as the Yangtze and Pearl Rivers [1, 2]. It is also a major global karst region, with karst areas comprising 53.4% of China's total [3]. The cold climate and karstification render the region's ecology extremely fragile [4].

Vegetation is crucial to ecosystems, global material cycling, energy balance, and water and carbon cycles [5-8]. It is especially important in preventing desertification in karst regions [9, 10]. Recent decades have seen the Yunnan-Guizhou Plateau affected by significant climate changes and human activities, resulting in a highly vulnerable ecology [10-12]. Considering the uncertain stability of vegetation changes, in-depth research on the region's vegetation dynamics and their response to climate change is essential for understanding its impact on terrestrial ecosystems.

The Vegetation Index, particularly the Normalized Difference Vegetation Index (NDVI), is vital for evaluating vegetation conditions and ecological changes. NDVI applications accurately reflect surface vegetation conditions and monitor long-term, widespread changes [13-18].

Current research on the Yunnan-Guizhou Plateau's vegetation focuses on the extensive Southwest and smaller scales, such as provincial and county levels, with few studies addressing overall NDVI changes and climate responses [3]. Tian et al. (2017) studied the spatiotemporal variation characteristics of vegetation cover in Guizhou Province and believed that the vegetation cover in Guizhou Province showed a continuous growth trend, and the growth rate of vegetation cover in karst areas was higher than that in non-karst areas [19]. Qiao et al. (2021) analyzed the spatiotemporal changes in vegetation cover in southwestern China from 2000 to 2016 and found that under the action of karst ecological restoration projects, the risk of rocky desertification can be effectively reduced [20]. Jiang et al. (2021) analyzed the spatiotemporal changes and potential influencing factors of NDVI under different altitudes and land use patterns in the southwestern region. The results showed that the critical elevation of NDVI was 3400 meters, and the responses of NDVI to climate change and human activities were different [21]. Xu et al. (2019) analyzed the influencing factors of vegetation mutation in the southwest region around 2001 and believed that on a 2.5-year time scale, vegetation mutation was influenced by climate change, especially temperature rise [22]. Xu et al. (2023) discovered a regional trend of vegetation improvement in southwest China from 2000 to 2020, with the change in NDVI being primarily influenced by meteorological factors such as minimum temperature, sunshine duration, and precipitation [2].

This study examines the vegetation status and changes in the Yunnan-Guizhou Plateau from 1981 to 2020, using trend and anomaly analysis with rainfall and temperature data. It aims to understand the past four decades' vegetation changes and their climate responses, providing scientific support for regional ecological protection and desertification management.

Research Area and Methodology

Overview of the Research Area

The Yunnan-Guizhou Plateau, situated in southwestern China (97.5°N-109.6°N, 21.0°E-29.3°E), encompasses the provinces of Yunnan and Guizhou. As depicted in Fig. 1, the region predominantly features

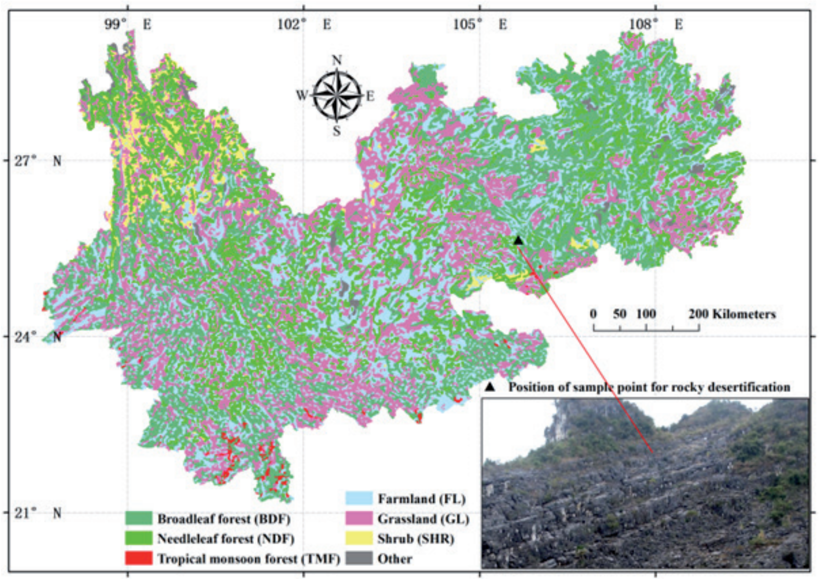

Fig. 1. Study area.

Broadleaf Forests (BDF), Needleleaf Forests (NDF), Tropical Monsoon Forests (TMF), Farmlands (FL), Grasslands (GL), and Shrubs (SHR), according to the China Vegetation Map (1:1,000,000) dataset. The plateau has a subtropical monsoon climate and is susceptible to severe desertification, as shown in Fig. 1. The dry season runs from November to March and the wet season from April to October, with temperature and precipitation peaking in July.

Data Sources and Processing

This study uses two NDVI products for analysis. The first, GIMMS NDVI, comes from the AVHRR GIMMS NDVI 3g.v1 dataset, covering 1982 to 34 years later. This dataset has a 15-day temporal resolution and a 1/12° spatial resolution. Monthly NDVI values are computed using the Maximum Value Composite method to mitigate the influence of cloud cover and aerosols.

The second NDVI product, MODIS NDVI, is derived from the MOD13A3 dataset and covers the period from 2001 to 2019. It offers a temporal resolution of one month and a spatial resolution of 1 km. Pixels averaging below 0.1 NDVI are considered non-vegetative. This study uses high-resolution meteorological data covering mainland China from 1982 to 2018, spanning 40 years. It has a 0.1° spatial resolution and uses monthly data for analysis. To align the datasets, vegetation and climate data were resampled to a 1/12° spatial resolution using nearest-neighbor interpolation. Land cover classifications are obtained from the China Vegetation Map (1:1,000,000) dataset. This dataset categorizes vegetation into seven distinct types: Broadleaf Forests (BDF), Needleleaf Forests (NDF), Tropical Monsoon Forests (TMF), Farmlands (FL), Grasslands (GL), and Shrubs (SHR). All other land cover is classified as 'other'.

Methodology

Ordinary Least Squares for Vegetation Dynamics Analysis

This study uses Ordinary Least Squares (OLS) with univariate linear regression to analyze pixel-level NDVI trends. The least squares method is extensively employed in grid-based trend analysis, enabling a clear reflection of vegetation change rates [23, 24]. The NDVI trend is calculated as follows:

$$\mathrm{S} = \frac{n\sum_{n}^{i=1} i\times N_i - \sum_{n}^{i=1} i \sum_{n}^{i=1} N_i}{n\sum_{n}^{i=1} i^2 - (\sum_{n}^{i=1} i)^2} \quad (1)$$

Here, n represents the years monitored by remote sensing, N_i is the NDVI value of the i-th growing season, and S is the regression slope. A positive value of S indicates an increasing trend in NDVI, and conversely, a negative value indicates a decreasing trend.

Anomaly Calculation Method

An anomaly is the deviation of a meteorological variable (like temperature or precipitation) from its long-term average in a specific area. In meteorology, anomalies indicate if data for a period is high or low compared to a long-term average (e.g., 30-year average) [25, 26]. The anomaly calculation formula is:

$$\mathrm{SA} = \frac{X-M}{S} \quad (2)$$

In this equation, X represents the variable at a specific time or period, M is the long-term average of that variable, and S is the standard deviation of the long-term variable.

Results and Analysis

Temporal Changes in Vegetation Growth and Hydrothermal Characteristics

Interannual Variability of NDVI

Fig. 2 shows the interannual variation trends of two NDVI products throughout the year and during the dry and rainy seasons. Vegetation cover on the Yunnan-Guizhou Plateau consistently increased during the study period. The annual GIMMS NDVI values varied from 0.62 to 0.67, showing a significant growth rate of 0.0009/a ($P<0.001$). During the datasets overlapping period, MODIS NDVI generally fell below GIMMS NDVI, with annual averages between 0.58 and 0.67. Importantly, MODIS NDVI's growth rates in the annual (0.0040/a, $P<0.001$), dry season (0.0044/a, $P<0.001$), and wet season (0.0037/a, $P<0.001$) were significantly higher than GIMMS NDVI's. Both NDVI datasets showed increasing trends during both the dry (November-March) and wet (April-October) seasons. GIMMS NDVI's growth rate remained consistent across seasons, with no significant increase during the dry season ($p = 0.002$); however, MODIS NDVI grew faster in the dry season (0.0044/a) than in the wet season (0.0037/a).

Anomaly Analysis of NDVI and Hydrothermal Parameters

Fig. 3 displays the standardized anomalies for NDVI and climatic parameters. Throughout the study, GIMMS NDVI showed a significant upward trend. From 1982 to 1994, GIMMS NDVI mostly showed negative anomalies annually and during both dry and wet seasons. The year 1990 stood out with a significantly higher positive NDVI anomaly compared to other years. Starting in 1995, GIMMS NDVI anomalies were predominantly positive, with notable declines in 2000, 2005, and 2012 (Fig. 3a).

Conversely, the upward trend of MODIS NDVI from 2001 to 2019 was more distinct. The year 2013 was a turning point, shifting from mainly negative to mostly positive anomalies. From 2013 onwards, the anomalies were positive, reaching a peak in 2017 (Fig. 3b).

Temperature anomalies exhibited a similar upward trend from 1982 to 2018. The year 1998 was a turning point, from mainly negative to mostly positive anomalies (Fig. 3c).

Precipitation showed no significant interannual pattern. However, periods of above-average precipitation occurred between 1994-2002, with 1987-1989

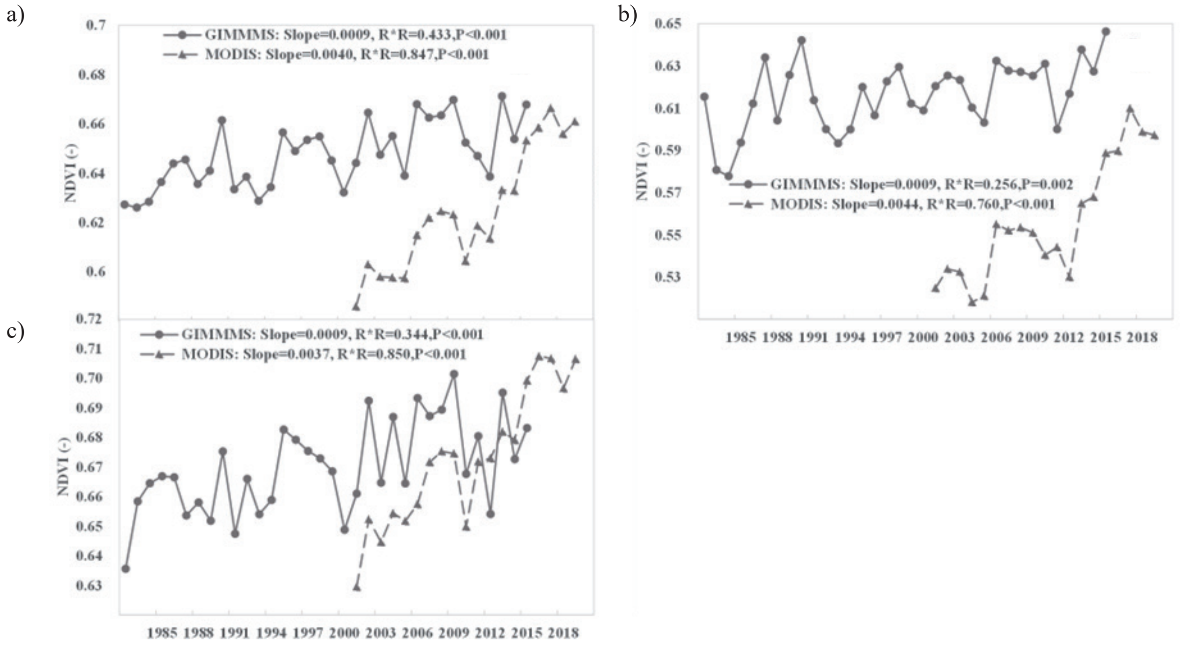

Fig. 2. Interannual variation trend of NDVI: a) annual, b) dry season, c) wet season.

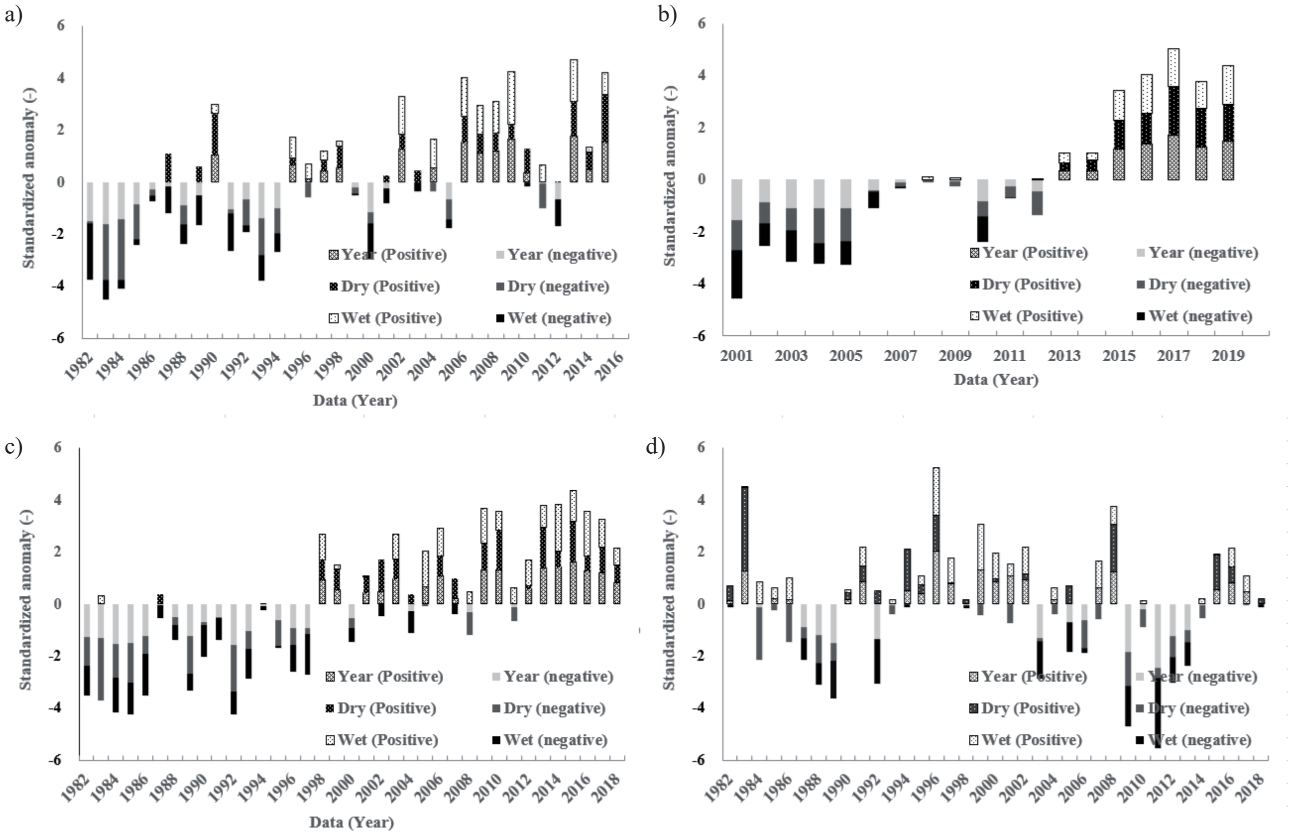

Fig. 3. Standardized anomalies of NDVI and climatic parameters: a) GIMMS NDVI, b) MODIS NDVI, c) temperature, d) precipitation.

and 2009-2013 being drier. The driest years for precipitation from 1982 to 2018 were 1989, 2009, and 2011 (Fig. 3d).

GIMMS NDVI anomaly trends closely matched those of temperature anomalies. Both showed mainly negative anomalies before 1995-1998, turning positive afterward. The notable NDVI spike in 1990 could be due to simultaneous increases in temperature and precipitation. The sharp decline in GIMMS NDVI in 2012 may be associated with the extended drought of 2009-2012, marking a 38-year precipitation low. Spatial Patterns of Vegetation and Hydrothermal Changes.

Spatial Distribution of Vegetation Growth Rate

Fig. 4 illustrates the spatial distribution of NDVI growth trends. From 1982 to 2015, the GIMMS NDVI trends across the Yunnan-Guizhou Plateau showed significant spatial heterogeneity. GIMMS NDVI growth rates ranged from -0.0057 to 0.0045 per annum (Fig. 4a). About 56.88% of the study area showed a statistically significant NDVI increase ($p<0.05$), indicating notable improvements in vegetation growth. Zhaotong and Qujing in Yunnan experienced the fastest vegetation growth. Conversely, a small portion (4.8%) showed a significant decline in NDVI ($p<0.05$), mainly

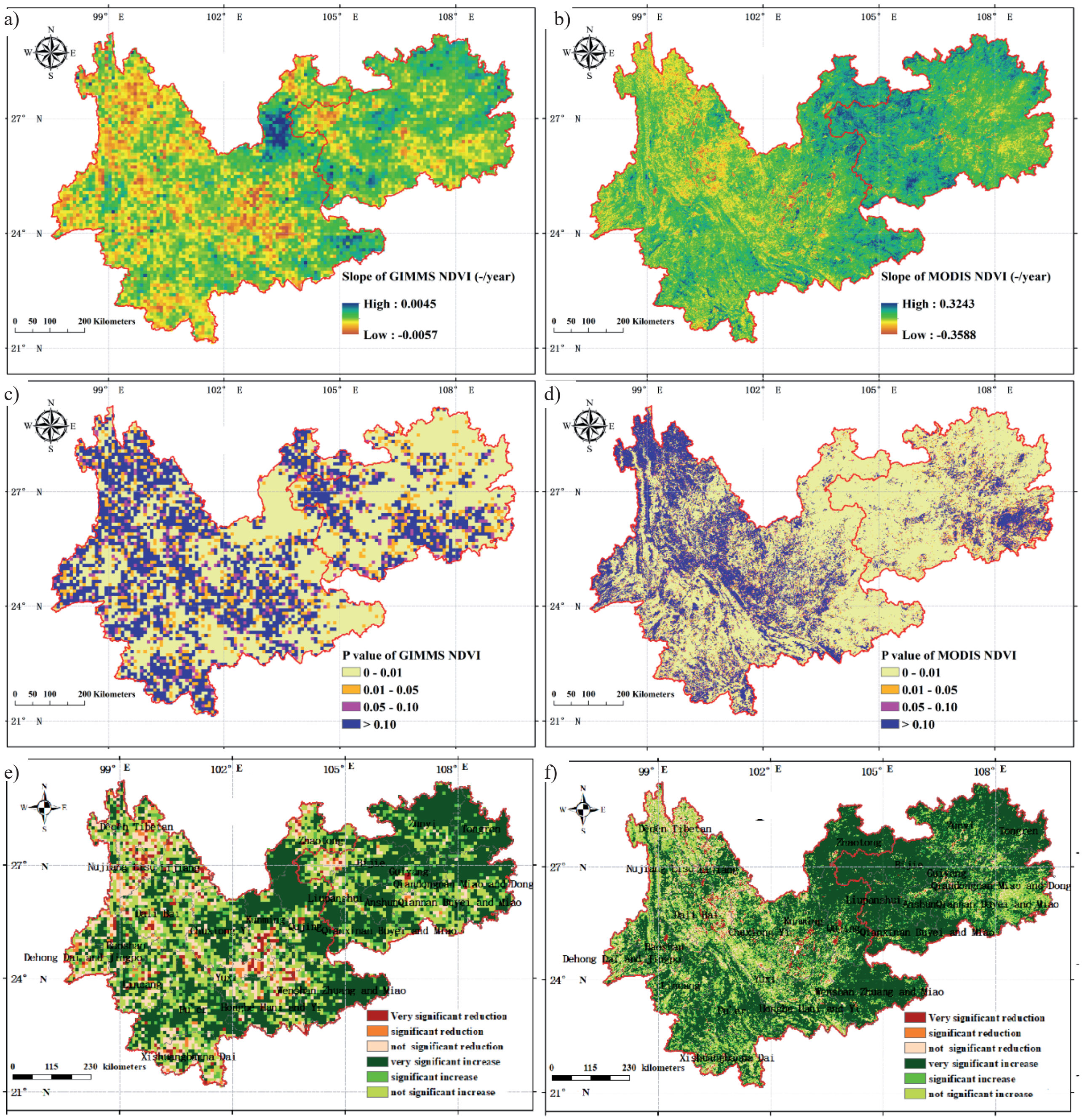

Fig. 4. Spatial distribution of vegetation NDVI growth trend.

in central and northwestern Yunnan and Bijie and Guiyang in Guizhou. Yuxi and Kunming in Yunnan faced the sharpest declines. For 2001-2019, MODIS NDVI growth rates ranged from -0.3588 to 0.3243 per annum (Fig. 4b). MODIS NDVI trends closely followed GIMMS NDVI, with 69.18% of pixels indicating a significant increase and 2.45% a significant decrease. The main difference between the two NDVI datasets appeared in western Guizhou, such as Bijie, where MODIS NDVI showed a significantly sharper increase compared to the more moderate trend of GIMMS NDVI.

Spatial Distribution of Hydrothermal Parameter Change Rates

Fig. 5 depicts the spatial distribution of temperature and precipitation change trends. Temperature change rates ranged from -0.022 to 0.131°C per annum (Fig. 5a). From 1982 to 2018, about 92.5% of pixels showed a statistically significant temperature increase ($p<0.05$), especially in central and western Yunnan (Baoshan, Dali, Kunming, Yuxi) and northeastern areas (Zhaotong). Only 1.9% of pixels showed a decreasing trend, mainly in central Guiyang and northeastern Tongren, Guizhou. Precipitation change rates ranged from -4.387 to 5.533 mm per annum (Fig. 5b). Regarding precipitation, approximately 37.6% of pixels had a positive slope, yet only 3.2% exhibited a significant increase ($p<0.05$), primarily in southern Yunnan and parts of central and eastern regions. Conversely, roughly 5.7% of pixels showed a significant decrease ($p<0.05$), scattered across areas like Dali Bai Autonomous Prefecture, Lincang, western Pu'er, and Honghe Hani and Yi Autonomous Prefecture in Yunnan. Compared

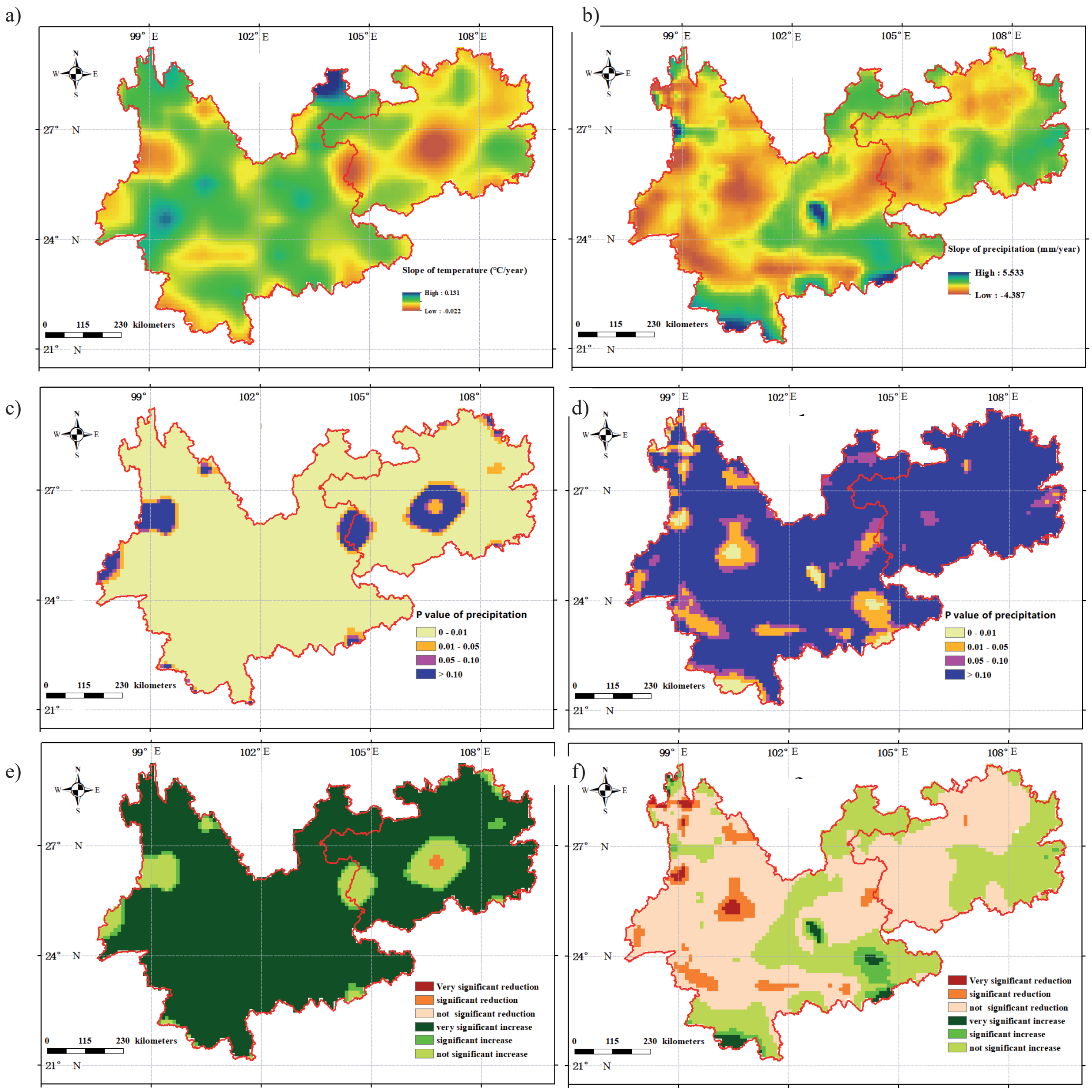

Fig. 5. Spatial distribution of temperature and precipitation change trend.

to temperature, precipitation trends were generally insignificant across most of the Yunnan-Guizhou Plateau over the last four decades.

Correlation Analysis Between NDVI and Hydrothermal Parameters

Fig. 6 shows the spatial distribution of correlations between NDVI and climate parameters. From a time-series perspective, GIMMS NDVI and temperature correlation coefficients ranged from -0.74 to 0.83 (Fig. 6a). About 50.78% of pixels showed a statistically significant positive correlation ($p<0.05$), mainly in most Guizhou and Yunnan regions. Of these, 38.6% had a highly significant correlation ($p<0.01$), especially in Guizhou, southwestern Yunnan (Lincang, western Pu'er, Honghe), and parts of eastern Yunnan (southern Zhaotong, northern Qujing). Only 4.15% of pixels exhibited a statistically significant negative correlation, with 2.31% showing a highly significant negative correlation, mostly in Yunnan.

GIMMS NDVI and precipitation correlation coefficients varied from -0.52 to 0.66 (Fig. 6d). Only approximately 6.74% showed a significant positive correlation and 0.95% a significant negative correlation, mainly in northwestern Yunnan. Most regions did not exhibit a significant correlation between NDVI and precipitation.

For MODIS NDVI, temperature correlations ranged from -0.82 to 0.87 (Fig. 6g). About 17.61% of pixels showed a significant positive correlation, primarily in southern and northeastern Guizhou and sporadically in northeastern and southern Yunnan. Conversely, approximately 4.33% of pixels exhibited a significant negative correlation, mainly in central and western Yunnan.

MODIS NDVI and precipitation correlations ranged from -0.62 to 0.82 (Fig. 6j). Around 10.78% of pixels

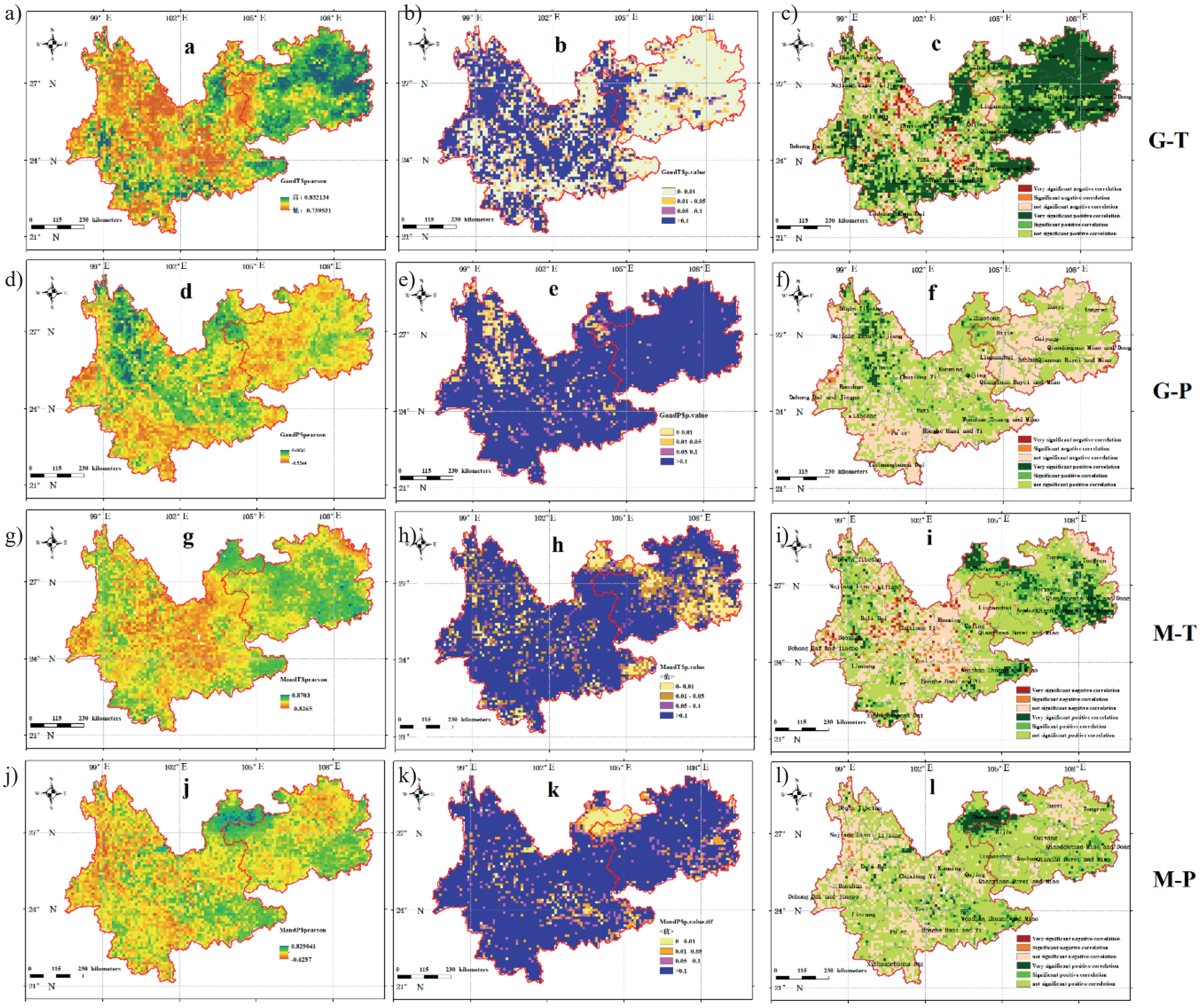

Fig. 6. Spatial distribution of correlation between NDVI and climate parameters (G refers to GIMMS NDVI, M refers to MODIS NDVI, T refers to temperature, P refers to precipitation).

displayed a significant positive correlation, mainly in Zhaotong in Yunnan and Bijie in Guizhou, and sporadically in central Yunnan and eastern Guizhou.

Overall, significantly more pixels showed a positive correlation between NDVI and temperature than those showing a negative one. Most of the negatively correlated pixels were localized in central Yunnan. The majority of regions showed a negative but statistically insignificant correlation between NDVI and precipitation. Areas with a significant positive correlation between NDVI and precipitation were relatively few and primarily located in Yunnan Province.

Both GIMMS and MODIS NDVI showed significant positive correlations with temperature year-round and in both dry and wet seasons. Specifically, during the dry season, GIMMS NDVI had a stronger positive correlation with temperature, marked by a 0.69 correlation coefficient (Fig. 7). The correlation between MODIS NDVI and temperature in the dry season was not statistically significant. Neither NDVI dataset exhibited a significant correlation with precipitation ($p<0.05$). The analysis indicates that temperature has a more significant impact on vegetation changes than precipitation.

Correlation Analysis of Different Vegetation Types with Hydrothermal Parameters

Fig. 8 displays the correlation between NDVI and climate parameters across various vegetation types. The correlation between NDVI and temperature differed among various vegetation types. Broadleaf Forests (BDF), Needleleaf Forests (NDF), and Tropical Monsoon Forests (TMF) all exhibited a statistically significant positive correlation with temperature. The correlation coefficients for these vegetation types ranged from 0.46 to 0.7, with Broadleaf Forests showing the strongest correlation with temperature.

In contrast, Farmlands (FL), Grasslands (GL), and Shrubs (SHR) demonstrated diverse relationships with temperature across the two NDVI datasets. The correlation patterns were not uniform, indicating that these vegetation types are influenced by a complex set of factors, possibly including human activities.

Interestingly, neither NDVI dataset showed a significant correlation with precipitation across any of the vegetation types. This suggests that precipitation may not be a primary driver of vegetation changes for these specific vegetation categories.

Discussion

Trends in Vegetation Change

Numerous studies have consistently reported an upward trend in vegetation NDVI across various spatial scales [27-32]. Globally, between 34% and 67% of the land area has experienced significant improvements in vegetation growth [33, 34]. Within China, between 53.8% and 77.7% of the land demonstrates an increasing NDVI trend, with a statistically significant increase in approximately 29.3% of the area [35-37]. In southwestern China, some studies have indicated that between 43.7% to 60.2% of the area exhibits an increasing NDVI trend [31, 38-41]. These findings align well with the results of the present study, which covers the period from 1982 to 2019. Specifically, 56.68% of areas show significant increases in GIMMS NDVI, and 69.18% in MODIS NDVI, respectively. These percentages are significantly

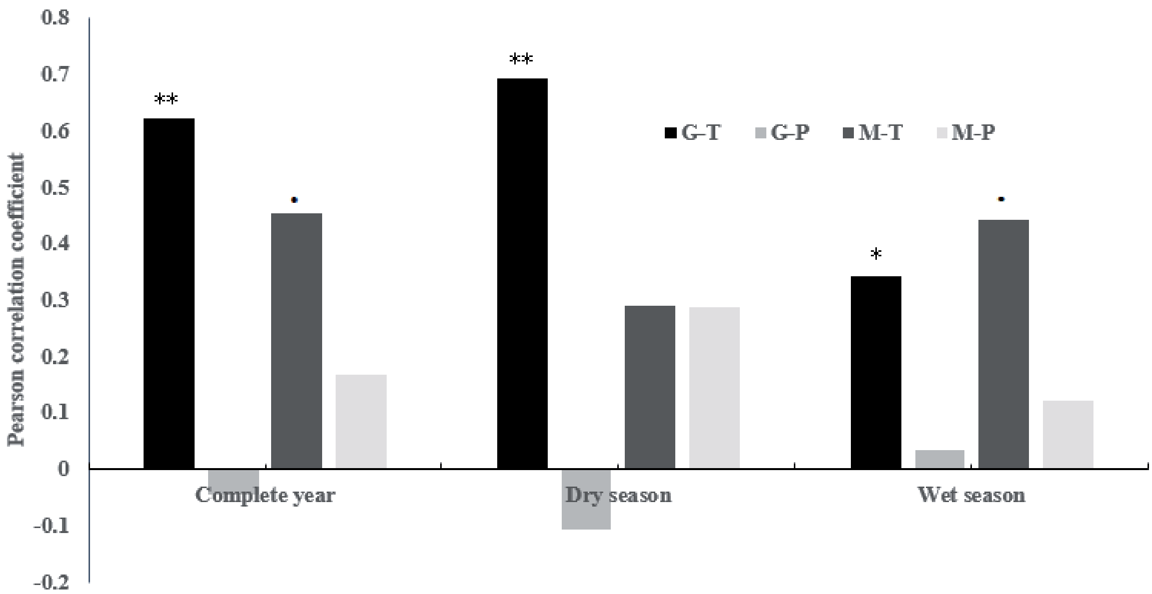

Fig. 7. Correlation between NDVI and climate parameters (G refers to GIMMS NDVI, M refers to MODIS NDVI, T refers to temperature, P refers to precipitation).

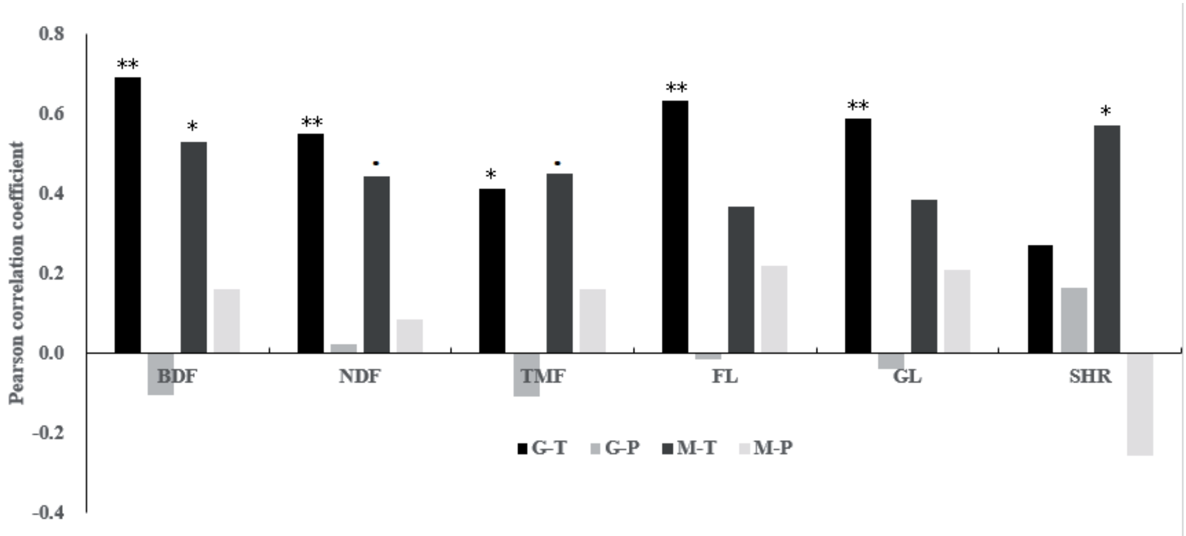

Fig. 8. Correlation between NDVI and climate parameters in different vegetation types (G refers to GIMMS NDVI, M refers to MODIS NDVI, T refers to temperature, P refers to precipitation).

higher than the average levels reported for the whole of China and its southwestern region.

This suggests that the Yunnan-Guizhou Plateau has undergone more substantial improvements in vegetation compared to other regions within the study timeframe. The estimated decadal increase rate of NDVI in the southwestern region ranges from 0.015 to 0.035 per decade [39, 42-45]. The trend analysis conducted for the Yunnan-Guizhou Plateau in this study revealed increase rates of 0.0009/a and 0.0040/a for GIMMS NDVI and MODIS NDVI, respectively, aligning with the findings of previous research.

In terms of spatial distribution, the area with a significant increase in MODIS NDVI is larger than that of GIMMS NDVI. The areas experiencing significant increases were primarily distributed in Bijie, Zhaotong, Liupanshui, southwest Guizhou, the northeast of Zunyi and Tongren, Wenshan, as well as parts of Lincang and Pu'er in the southwest. One contributing factor is the favorable water and heat conditions that promote vegetation growth in places like Zhaotong [46, 47]. Another reason is the implementation of measures to combat stony desertification through initiatives such as returning farmland to forest, mountain closure, and afforestation projects, as well as soil and water conservation efforts [48]. These actions have significantly improved the status of vegetation growth in central and western parts of Bijie, Liupanshui, and southwest Guizhou where stony desertification is concentrated within karst areas.

The areas exhibiting no noticeable changes are mainly located in southeast Guizhou, Xishuangbanna, Dali, Nujiang, Diqing, and central Yunnan. These areas have high vegetation coverage and have not been seriously damaged, such as tropical rainforests in Xishuangbanna and primary forests in southeast Guizhou.

On the other hand, there has been a significant decrease observed mainly in Kunming, Dali Qujing, Guiyang, and Anshun. The urbanization expansion in these cities has led to the reduction of vegetation area, particularly evident in ecologically fragile karst areas.

Impact of Hydrothermal Conditions on Vegetation Change

Role of Temperature and Precipitation

Global warming and regional precipitation shifts have been well-documented. Studies have revealed a notable warming trend since 1960 in Guizhou Province [40, 49]. This study, covering the Yunnan-Guizhou Plateau from 1982 to 2019, reveals that 92.5% of the area experienced a significant temperature increase, though precipitation trends are inconclusive.

Precipitation and temperature are considered the two most crucial climatic factors affecting vegetation dynamics [50], as they influence plant growth and distribution through control of photosynthesis and respiration [30, 51, 52]. Within suitable ranges, temperature and precipitation promote physiological and biochemical plant reactions [53]. The correlation between NDVI and climate factors varies across different times and spaces. A previous study found that in temperate and cold Eurasia, a decline in summer NDVI was related to decreased precipitation, increased spring temperatures enhanced vegetation growth, and summer and seasonal vegetation growth were driven by precipitation [17, 54]. Chen et al (2021). demonstrated that in western Xinjiang, temperature significantly affects NDVI in high-precipitation areas, whereas precipitation is a key factor in low-precipitation areas [43]. In the humid climate of the southwestern region, previous studies highlight that temperature has a more dominant influence on vegetation growth than precipitation does [31, 39, 41, 42, 55-57]. Significantly, in this research, 50.78% of GIMMS and 17.61% of MODIS NDVI pixels show a positive correlation with temperature. This aligns with previous findings that temperature impacts key physiological processes such as photosynthesis, respiration, and nutrient utilization [58-60].

Regional Variability and Anomalies

Interestingly, 4.15% of GIMMS NDVI pixels and 4.33% of MODIS NDVI pixels exhibit a significant negative correlation with temperature. These areas, often susceptible to drought, include Lijiang, Kunming, Chuxiong, Dali, Yuxi, northern Honghe, and Dehong [61, 62]. Elevated temperatures in these regions can exacerbate water evaporation, reducing water available for vegetation growth and thereby stressing vegetation [17]. Zhe et al. (2021) found that rising temperatures could inhibit vegetation growth in South Tibet [61], mainly due to enhanced evapotranspiration and permafrost degradation from climate warming, potentially creating soil temperature, moisture, and nutrient imbalances [63-65]. Previous research identified a significant negative correlation between NDVI and temperature in the middle and southern AHRB, areas with drought-prone grasslands [17]. These previous researches suggest that under conditions of low precipitation, rising temperatures may inhibit plant growth.

Our study identifies a positive correlation between NDVI and precipitation in 6.74% and 10.78% of areas, respectively, primarily in Kunming, Dali, Yuxi, northern Honghe, Wenshan, Diqing, and Zhaotong. The area in Yunnan where NDVI exhibits a negative correlation with temperature overlaps with the area where NDVI shows a positive correlation with precipitation. These findings imply that in arid and hot climates, even minimal precipitation can significantly benefit vegetation growth.

Dataset Discrepancies and Human Influence

The GIMMS and MODIS NDVI datasets display discrepancies. While GIMMS NDVI values are typically higher, MODIS NDVI shows a faster growth rate, broader growth area, and more pronounced trend than GIMMS NDVI. The proportion of MODIS NDVI pixels exhibiting significant changes is 71.63%, among which, the proportion of NDVI pixels showing a significant correlation with temperature and precipitation is 33.42%. Other regions experiencing significant changes may be attributed to anthropogenic influences. Yang et al. (2022) identified human activities as the dominant factor in vegetation cover improvement and degradation from 2001 to 2019, with average influences of 62% and 59%, respectively [55]. Since the year 2000, China has launched various ecological restoration projects [44, 57, 66], possibly explaining the rapid increase in MODIS NDVI and its weaker correlation with temperature. The correlation between MODIS NDVI and temperature for the entire year and dry season is comparatively weaker compared to that observed between GIMMS NDVI and temperature. GIMMS NDVI encompasses a broader temporal range than MODIS NDVI. From a statistical standpoint, the impact of hydrothermal conditions on NDVI mitigates the impact of anthropogenic activities.

Vegetation Type-Specific Correlations

Vegetation types exhibit diverse relationships between NDVI and temperature. Broadleaf forests, needleleaf forests, and tropical monsoon forests all show a significant positive correlation with temperature across both NDVIs. Conversely, farmlands, grasslands, and shrubs show varied temperature relationships in the two NDVIs, possibly reflecting their greater sensitivity to human activities. Compared to forests, farmlands, grasslands, and shrubs are more susceptible to human activities. Forest ecosystems are more stable, with hydrothermal conditions predominantly influencing changes [37, 43].

The primary focus of this study is the impact of hydrothermal conditions on vegetation growth. Future research will quantitatively evaluate the effects of human activities and extreme climatic events to clarify the ecological changes' driving mechanisms in the Yunnan-Guizhou region.

Conclusions

This study investigates vegetation dynamics on the Yunnan-Guizhou Plateau from 1982 to 2019. By employing trend and anomaly analyses, and juxtaposing these with temperature and precipitation datasets, we have illuminated the intricate interplay between vegetation changes and hydrothermal shifts over the past four decades. Key findings include:

1. NDVI Seasonal Trends: Both GIMMS (1982-2015, 0.0009/a) and MODIS (2001-2019, 0.0040/a) datasets reveal a significant upward trend. Importantly, MODIS NDVI's growth rate exceeds that of GIMMS, indicating improved vegetation vitality in the Yunnan-Guizhou region after 2001. Since 2000, China has implemented a series of ecological restoration projects, resulting in an intensified impact of anthropogenic activities on vegetation improvement, which can explain the accelerated growth of vegetation after 2001.

2. Spatial Dynamics: NDVI trends across the Yunnan-Guizhou Plateau show significant spatial heterogeneity. Notably, 56.88% (GIMMS NDVI) and 69.18% (MODIS NDVI) of the area show significant vegetation growth. Notably, the trend of vegetation growth in Guizhou surpassed that observed in Yunnan. Impressively, 92.5% of the study area experiences a temperature increase, while precipitation trends remain stable.

3. Hydrothermal Interactions: NDVI fluctuations reflect temperature anomalies, emphasizing temperature's critical role. Certain years suggest drought-induced NDVI decreases, such as in 2012. Both NDVI datasets correlate with temperature annually and seasonally but show little correlation with precipitation. Approximately 50.78% (GIMMS) and 17.61% (MODIS) of pixels show a positive correlation with temperature. Meanwhile, 4.15% (GIMMS) and 4.33% (MODIS) of pixels, especially in Yunnan's drought-prone areas, exhibit a negative correlation with temperature, indicating increased evaporation and subsequent vegetation stress. The areas with Positive correlations between NDVI and precipitation count for 6.74% and 10.78%, mainly in central Yunnan and the Bijie region, where the climate is dry and hot, precipitation benefits vegetation growth.

4. Vegetation Variability: Broadleaf, needleleaf, and tropical monsoon forests maintain a consistent positive temperature correlation in both NDVI datasets. Conversely, farmlands, grasslands, and shrubs show diverse temperature relationships, likely influenced by increased human activity.

Acknowledgments

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Conflicts of Interest

The authors declare no conflict of interest.

References

1. GE W.Y., HAN J.Q., ZHANG D.J., WANG F. Divergent impacts of droughts on vegetation phenology and productivity in the Yungui Plateau, southwest China. Ecological indicators, **127**, 107743, **2021**.
2. XU Y., DAI Q.Y., HUANG W.T., PAN Y.C., ZHENG Z.W., GUO Z.D. Spatio-temporal variation in vegetation cover and its driving mechanism exploration in southwest China from 2000 to 2020. Environmental Science, **44** (1), 323, **2023**.
3. LIU Z.J., ZENG Y.L., YAN L., TAN W. Spatial-temporal variation characteristics of the vegetation NVDI in Yunnan- Guizhou Plateau from 2001 to 2014. Journal of Mountain Agriculture And Biology, **37** (1), 032, **2018**.
4. WANG Z.J., LIU S.J., LI J.H., PAN J.L., WU J.L., RAN J., SU Y. Remarkable improvement of ecosystem service values promoted by land use/land cover changes on the Yungui Plateau of China during 2001-2020. Ecological Indicators, **142**, 109303, **2022**.
5. VERRALL B., PICKERING C.M. Alpine vegetation in the context of climate change: A global review of past research and future directions. Science of The Total Environment, **748**, 141344, **2020**.
6. BEAMISH A., RAYNOLDS M.K., EPSTEIN H., FROST G.V., MACANDER M.J., BERGSTEDT H., BARTSCH A., KRUSE S., MILES V., TANIS C.M. Recent trends and remaining challenges for optical remote sensing of Arctic tundra vegetation: A review and outlook. Remote Sensing of Environment, **246**, 111872, **2020**.
7. JIN K., WANG F., ZONG Q., QIN P., LIU C. Impact of variations in vegetation on surface air temperature change over the Chinese Loess Plateau. Science of The Total Environment, **716**, 136967, **2020**.
8. QU L., HAN W., LIN H., ZHU Y., ZHANG L. Estimating vegetation fraction using hyperspectral pixel unmixing method: a case study of a karst area in China. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, **7** (11), 4559, **2014**.
9. TANG J., TANG X., QIN Y., HE Q., YI Y., JI Z.L. Karst rocky desertification progress: Soil calcium as a possible driving force. Science of The Total Environment, **649**, 1250, **2019**.
10. JIANG Z., LIAN Y., QIN X. Rocky desertification in Southwest China: Impacts, causes, and restoration. Earth-Science Reviews, **132**, 1, **2014**.
11. WANG K., ZHANG C., CHEN H., YUE Y., ZHANG W. Karst landscapes of China: patterns, ecosystem processes and services. Landscape Ecology, **34**, 2743, **2019**.
12. HONG L., HUANG Y., PENG S. Monitoring the trends of water-erosion desertification on the Yunnan-Guizhou Plateau, China from 1989 to 2016 using time-series Landsat images. PLoS One, **15** (2), e0227498, **2020**.
13. HUANG X., ZHANG T., YI G., HE D., ZHOU X., LI J., BIE X., MIAO J. Dynamic changes of NDVI in the growing season of the Tibetan Plateau during the past 17 years and its response to climate change. International Journal of Environmental Research and Public Health, **16** (18), 3452, **2019**.
14. ZHOU Q., LUO Y., ZHOU X., CAI M., ZHAO C. Response of vegetation to water balance conditions at different time scales across the karst area of southwestern China-A remote sensing approach. Science of The Total Environment, **645**, 460, **2018**.
15. PINZON J.E., TUCKER C.J. A non-stationary 1981-2012 AVHRR NDVI3g time series. Remote Sensing, **6**, 6929, **2014**.
16. CHU H., VENEVSKY S., WU C., WANG M. NDVI-based vegetation dynamics and its response to climate changes at Amur-Heilongjiang River Basin from 1982 to 2015. Science of The Total Environment, **650**, 2051, **2019**.
17. HUANG S., TANG L., HUPY J.P., WANG Y., SHAO G. A commentary review on the use of normalized difference vegetation index (NDVI) in the era of popular remote sensing. Journal of Forestry Research, **32** (1), 1, **2021**.
18. LI S., XU L., JING Y., YIN H., LI X., GUAN X. High-quality vegetation index product generation: A review of NDVI time series reconstruction techniques. International Journal of Applied Earth Observation and Geoinformation, **105**, 102640, **2021**.
19. TIAN Y., BAI X., WANG S., QIN L.Y., LI Y. Spatial-temporal changes of vegetation cover in Guizhou Province, Southern China. Chinese Geographical Science, **27** (1), 25, **2017**.

20. QIAO Y., JIANG Y., ZHANG C. Contribution of karst ecological restoration engineering to vegetation greening in southwest China during recent decade. Ecological Indicators, **121**, 107081, **2021**.
21. JIANG S., CHEN X., SMETTEM K., WANG T.J. Climate and land use influences on changing spatiotemporal patterns of mountain vegetation cover in southwest China. Ecological Indicators, **121**, 107193, **2021**.
22. XU X., LIU H., LIN Z., JIAO F., GONG H. Relationship of abrupt vegetation change to climate change and ecological engineering with multi-timescale analysis in the karst region, southwest China. Remote Sensing, **11** (13), 1564, **2019**.
23. ZHANG D., JIA Q., WANG P., ZHANG J., HOU X., LI X., LI W. Analysis of spatial variability in factors contributing to vegetation restoration in Yan'an, China. Ecological Indicators, **113**, 106278, **2020**.
24. WANG Y., GAO W. Responses of NDVI to climate factors in Inner Mongolia using geographically weighted regression. IOP Conference Series: Earth and Environmental Science. IOP Publishing, **568** (1), 012012, **2020**.
25. BI J., MYNENI R., LYAPUSTIN A., WANG Y.J., PARK T., CHI C., YAN K. KNYAZIKHIN Y. Amazon forests' response to droughts: A perspective from the MAIAC product. Remote Sensing, **8** (4), 356, **2016**.
26. WANG J, LIU Y, DING Y. Potential remote forcing of North Atlantic SST tripole anomalies on the seesaw haze intensity between late winter months in the North China plain: A case study. Atmospheric Science Letters, **24** (9), e1170, **2023**.
27. CHENG L., ZHANG Y., SUN H. Vegetation cover change and relative contributions of associated driving factors in the ecological conservation and development zone of Beijing, China. Polish Journal of Environmental Studies, **29** (1), 53, **2020**.
28. FENG J., DONG B., QIN T., LIUS., ZHANG J., GONG X. Temporal and spatial variation characteristics of NDVI and its relationship with environmental factors in Huangshui River basin from 2000 to 2018. Polish Journal of Environmental Studies, **30** (4), 3043, **2021**.
29. GUO J., WANG K., WANG T., BAI N., ZHANG H., CAO Y., LIU H. Spatiotemporal variation of vegetation NDVI and its climatic driving forces in global land surface. Polish Journal of Environmental Studies, **31** (4), 3541, **2022**.
30. DUAN C., LI J., CHEN Y., DING Z., MA M., XIE J., YAO L., TANG X. Spatiotemporal dynamics of terrestrial vegetation and its driver analysis over southwest China from 1982 to 2015. Remote Sensing, **14** (10), 2497, **2022**.
31. WEI Y., SUN S., LIANG D., JIA Z. Spatial–temporal variations of NDVI and its response to climate in China from 2001 to 2020. International Journal of Digital Earth, **15** (1), 1463, **2022**.
32. RAFIQUE R., ZHAO F., JONG R.D., ZENG N., ASRAR G.R. Global and regional variability and change in terrestrial ecosystems net primary production and NDVI: A model-data comparison. Remote Sensing, **8** (3), 177, **2016**.
33. YANG Y.J., WANG S.J., BAI X.Y., TAN Q., LI Q., WU L.H., TIAN S.Q., HU Z.Y., LI C.J., DENG Y.H. Factors affecting long-term trends in global NDVI. Forests, **10** (5), 372, **2019**.
34. EASTMAN J., FLORENCIA S., ELIA M., JOHN R., ASSAF A. Global trends in seasonality of Normalized Difference Vegetation Index (NDVI), 1982-2011. Remote Sensing, **5** (10), 4799, **2013**.
35. WANG Z., LU Z., CUI G. Spatiotemporal variation of land surface temperature and vegetation in response to climate change based on NOAA-AVHRR data over China. Sustainability, **12** (9), 3601, **2020**.
36. ZHANG Y., YE A. Spatial and temporal variations in vegetation coverage observed using AVHRR GIMMS and Terra MODIS data in the mainland of China. International Journal of Remote Sensing, **41** (11), 4238, **2020**.
37. HE Y.L., LI T.Y., XIONG Q.L., YU L. Spatio-temporal patterns of vegetation coverage and response to hydrothermal factors in Yunnan Province, Chin. Acta Ecologica Sinica, **38** (24), 8813, **2018**.
38. CAO Y., QIAN YL., SUN Y.L., QIAN S.A., ZHANG Y.P., YAN H. Spatial-temporal variations of forest vegetation and climatic driving force analysis in southwest China based on MODIS NDVI and climate data. Ecology and Environmental Sciences, **29** (5), 857, **2020**.
39. WEI X., ZHOU Q., LUO Y., CAI M., ZHOU X., YAN W., PENG D., ZHANG J. Vegetation dynamics and its response to driving factors in typical karst regions, Guizhou Province, China. Frontiers of Earth Science, **15**, 167, **2021**.
40. XUE X., WANG Z.J., HOU S.S. NDVI-Based vegetation dynamics and response to climate changes and human activities in Guizhou Province, China. Forests, **14** (4),753, **2023**
41. HOU W., GAO J., WU S., DAI E. Interannual variations in growing-season NDVI and its correlation with climate variables in the southwestern karst region of China. Remote Sensing, **7** (9), 11105, **2015**.
42. XIAO J.Y., WANG S.J., BAI X.Y., ZHOU D.Q., TIAN Y.C., LI Q., WU L.H., QIAN Q.H, CHEN F., ZENG C. Determinants and spatial-temporal evolution of vegetation coverage in the karst critical zone of South China. Acta Ecologica Sinica, **38** (24), 8799, **2018**.
43. CHEN W., BAI S., ZHAO H., HAN X., LI L. Spatiotemporal analysis and potential impact factors of vegetation variation in the karst region of Southwest China. Environmental Science and Pollution Research, **28** (43), 61258, **2021**.
44. YANG C.P., WANG Y.Q., WU J.J., SHEN H.Z., MA X.Y. Spatiotemporal evolution and lag effect of drought and vegetation dynamics in Southwest China. Applied Ecology And Environmental Research, **20** (4), 3447, **2022**.
45. GU F., GOU X.H., DENG Y., SU J.J., LIN W., YU A.L. Analysis of temperature variations over the Yunnan-Guizhou Plateau from 1960 to 2014. Journal of Lanzhou University Natural Science, **54**, 721, **2018**.
46. LI Y.S., YUAN W.H., SUN J.H., MA W.Q., CHEN X.H., LIAN Y. Temporal and Spatial Distribution of Hourly Precipitation in Rainy and Dry Seasons over Yunnan Province, Plateau and Mountain Meteorology Research, **41** (03), 24, **2021**.
47. ZHU D., YANG Q., XIONG K., XIAO H. Spatiotemporal variations in daytime and night-time precipitation on the Yunnan–Guizhou Plateau from 1960 to 2017. Atmosphere, **13** (3), 415, **2022**.
48. HE B., CHEN A., WANG H., WANG Q. Dynamic response of satellite-derived vegetation growth to climate change in the Three North Shelter Forest Region in China. Remote Sensing, **7** (8), 9998, **2015**.
49. ZHANG Q. Quantitative analysis of spatial and temporal change and dynamics of NDVI in Hunan province from 2000 to 2017. Central South University of Forestry & Technology, **2020**. [In Chinese].
50. YANG X., SHAO X.H., MAO X.Y., DING F.Z., YUAN Y.B. Spatio-temporal variation of evaporation under

a warming climate in Southwest Guizhou Plateau of China. Fresenius environmental bulletin, **29** (20), 9125, **2020**.
51. ZHANG Q.B., LUO J., ZHOU X.L., WANG G.J. Dynamic change of NDVI and response to climate impact from 2000 to 2017 in Hunan province. Journal of Central South University of Forestry & Technology, **40** (12), 94, **2020**.
52. XU H.J., WANG X.P., YANG T.B. Trend shifts in satellite-derived vegetation growth in Central Eurasia, 1982-2013. Science of the Total Environment. **579**, 1658, **2017**.
53. CUI L.L., SHI J., YANG Y.M., FAN W.Y. Ten-day response of vegetation NDVI to the variations of temperature and precipitation in eastern China. Acta Geographica Sinica, **64** (07), 850, **2009**.
54. ZHOU J., MA M., XIAO Q., WEN J. Vegetation dynamics and its relationship with climatic factors in southwestern China. Remote Sensing Technology and Application, **32** (5), 966, **2017**.
55. ZHANG Y., ZHANG X., LIU S. Correlation analysis on normalized difference vegetation index (NDVI) of different vegetation and climatic factors in Southwest China. China Journal of Applied Ecology, **22** (2), 323, **2011**.
56. YANG H., HU J., ZHANG S., XIONG L., XU Y. Climate variations vs. human activities: distinguishing the relative roles on vegetation dynamics in the Three Karst Provinces of Southwest China. Frontiers in Earth Science, **10**, 799493, **2022**.
57. SUN J., ZHOU T.C., LIU M., CHEN Y.C., LIU G.H., XU M., SHI P.L., PENG F., TSUNEKAWA A., LIU Y., WANG X.D., DONG S.K., ZHANG Y.J., LI Y.N. Water and heat availability are drivers of the aboveground plant carbon accumulation rate in alpine grasslands on the Tibetan plateau. Global ecology and biogeography, **29** (1), 50, **2020**.
58. WAN S., HUI D., WALLACE L., LUO Y. Direct and indirect effects of experimental warming on ecosystem carbon processes in a tallgrass prairie. Glob. Biogeochemical Cycles, **19** (2), 1, **2005**.
59. DRAGONI D., SCHMID H.P., WAYSON C.A., POTTER H., GRIMMOND C.S.B., RANDOLPH J.C. Evidence of increased net ecosystem productivity associated with a longer vegetated season in a deciduous forest in south-central Indiana, USA. Global Change Biology, **17** (2), 886, **2011**.
60. WANG M., DING Z., WU C., SONG L., MA M., YU P., LU B., TANG X. Divergent responses of ecosystem water-use efficiency to extreme seasonal droughts in Southwest China. Science of The Total Environment, **760**, 143427, **2021**.
61. TANG H., WEN T., SHI P., QU S., ZHAO L., LI Q. Analysis of characteristics of hydrological and meteorological drought evolution in Southwest China. Water, **13** (13), 1846, **2021**.
62. ZHE M., ZHANG X. Time-lag effects of NDVI responses to climate change in the Yamzhog Yumco Basin, South Tibet. Ecological Indicators, **124**, 107431, **2021**.
63. YI S., WANG X., QIN Y., XIANG B., DING Y. Responses of alpine grassland on Qinghai-Tibetan plateau to climate warming and permafrost degradation: A modeling perspective. Environmental Research Letters, **9** (7), 074014, **2014**.
64. WANG X., YI S., WU Q., YANG K., DING Y. The role of permafrost and soil water in distribution of alpine grassland and its NDVI dynamics on the Qinghai-Tibetan Plateau. Global and Planetary Change, **147**, 40, **2016**.
65. ZHANG C., QI X., WANG K., ZHANG M., YUE Y. The application of geospatial techniques in monitoring karst vegetation recovery in southwest China: A review. Progress in Physical Geography, **41** (4), 450, **2017**.
66. XU J.T., YIN R.S., LI Z., LIU C. China's ecological rehabilitation: Unprecedented efforts, dramatic impacts, and requisite policies. Ecological Economics, **57** (4), 595, **2006**.
67. LIU J., LI S., OUYANG Z., TAM C., CHEN X. Ecological and socioeconomic effects of China's policies for ecosystem services. Proceedings of the National Academy of Sciences of the USA, **105**, 9477, **2008**.