

Article

Analysis of Spatiotemporal Changes in NDVI-Derived Vegetation Index and Its Influencing Factors in Kunming City (2000 to 2020)

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Abstract

Vegetation is a fundamental component of ecosystems and plays a vital role in maintaining ecological processes. It contributes to soil conservation, climate regulation, and landscape quality. Kunming, widely known as the “Spring City,” relies heavily on vegetation to sustain its ecological and social environment. This study employs moderate resolution imaging spectroradiometer (MODIS) and Normalized Difference Vegetation Index (NDVI) data in combination with temperature, precipitation, population, and gross domestic product (GDP) records to analyze the spatiotemporal dynamics and driving factors of NDVI-derived vegetation index in Kunming from 2000 to 2020 using trend and correlation analyses. We derived fractional vegetation coverage (FVC) from MODIS NDVI using the pixel dichotomy model, analyzed its temporal trends with linear regression, and applied pixel-wise Pearson correlation analysis to identify the spatial relationship between FVC and precipitation. The main findings can be summarized as follows: (1) The NDVI-derived vegetation index pattern in Kunming is generally higher in the west than in the east and higher in mountainous areas than in plains and basins. From 2000 to 2020, overall NDVI-derived vegetation index increased, with the mean NDVI rising from 0.48 to 0.545. Notably, the NDVI values in 2010 and 2012 declined sharply, likely due to drought conditions caused by reduced rainfall in the preceding years. (2) During the study period, 26.86% of the area showed moderate (NDVI slope: 0.005–0.016) improvement and 10.35% showed significant (NDVI slope: 0.016–0.063) improvement, while 10.28% exhibited degradation. Spatially, improvements were concentrated in Xundian County, parts of Dongchuan District, northern Luquan County, and northern border areas adjoining Yiliang and Shilin Counties. Areas with clear degradation were primarily located in Kunming’s main urban area and along the corridor from the airport to Songming. (3) Correlation analysis revealed that 53.3% of areas exhibited a positive relationship between temperature and NDVI-derived vegetation index, while 18.6% showed a significant negative correlation, mainly in the lower Pudu River basin, the Fumin–Luquan border, and the basin areas of Songming and Shilin Counties. This negative relationship may be attributed to increased evapotranspiration under higher temperatures, which exacerbates soil moisture loss and imposes drought stress on vegetation, thereby inhibiting plant growth. Similarly, 53% of areas showed a positive correlation between precipitation and FVC, whereas only 8.3% showed a significant negative correlation, underscoring the strong influence of precipitation on vegetation dynamics in Kunming. (4) Over the past two decades, Kunming’s GDP increased tenfold. In comparison with NDVI-derived vegetation index data for the same period, this indicates that areas of higher GDP are often associated with lower NDVI-derived vegetation index.



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Keywords: Kunming city; NDVI-derived vegetation index; temporal and spatial changes; driving factors

1. Introduction

Vegetation coverage plays a fundamental role in regulating regional climate, carbon balance, and ecosystem services. Understanding how climate and anthropogenic factors influence vegetation coverage dynamics is essential for elucidating terrestrial ecosystem responses to environmental change and for promoting sustainable land management. Such research provides critical insights for developing ecological protection strategies, maintaining ecological balance, and advancing the sustainable development of human societies [1]. The Normalized Difference Vegetation Index (NDVI) is widely recognized as the most effective indicator for assessing plant growth status. Because of its strong correlation with NDVI-derived vegetation index, the NDVI is extensively employed in studies examining surface vegetation change. It serves not only as a reliable measure of vegetation cover but also as an important tool for characterizing vegetation growth and activity patterns [2].

Guo et al. employed the pixel dichotomy model and partial correlation analysis to examine changes in NDVI-derived vegetation index and its driving factors on the Qinghai–Tibet Plateau from 2001 to 2020. Their results showed that NDVI-derived vegetation index was positively correlated, to varying degrees, with climatic factors, while human activities primarily contributed to improvements in NDVI-derived vegetation index [3]. Liu et al. analyzed the main factors influencing NDVI-derived vegetation index in Southwest China, incorporating temperature, precipitation, and Digital Elevation Model (DEM) data. Their results indicated that precipitation promotes NDVI-derived vegetation index, whereas temperature has regionally variable effects. In addition to climatic factors, human activities exert substantial effects on NDVI-derived vegetation index. Specifically, policies converting cropland to forest significantly increased NDVI-derived vegetation index in some areas, while urbanization processes reduced NDVI-derived vegetation index in some areas as well as vegetation in urban zones [4].

Wu investigated dynamic NDVI-derived vegetation index changes in Hefei City using Landsat imagery and assessed the responses of NDVI-derived vegetation index to meteorological, topographic, and social activity factors. Their study concluded that socioeconomic factors were the dominant drivers of vegetation dynamics in Hefei [5]. Zhao et al. examined the dry-hot valley of the Jinsha River using MODIS-NDVI data and found that NDVI-derived vegetation index was weakly but positively correlated with temperature and precipitation. Human activities were identified as key contributors to vegetation improvements, while altitude exerted a significant influence on spatial variation. NDVI-derived vegetation index in this region exhibited a complex pattern, with low and low–medium coverage initially increasing, then decreasing, and increasing again along the elevational gradient [6].

Kui et al. analyzed NDVI-derived vegetation index changes and driving forces in the Inner Mongolia grassland region using Landsat 7/8 data. Their results indicated that precipitation was the dominant factor shaping spatial heterogeneity and exerted the strongest synergistic effects when combined with soil type, land use, and temperature [7]. Focusing specifically on Kunming, Li and Hu employed the Google Earth Engine (GEE) platform to investigate NDVI-derived vegetation index from 1998 to 2018. They found that areas of relatively high coverage were concentrated in the northeastern, northern, and western parts of the city, whereas low coverage was primarily observed in the flat terrain of

the main urban area. Overall, NDVI-derived vegetation index in Kunming increased during the 30-year period [8]. Similarly, Xu et al. studied vegetation distribution in Kunming and reported that altitude and slope strongly influenced spatial heterogeneity [9]. Chen et al. used remote sensing data to assess NDVI-derived vegetation index in Kunming from 1988 to 2010. Their findings revealed a decreasing trend between 1988 and 2000, largely attributed to urban expansion, followed by an increase from 2000 to 2010 [10].

Building on these prior studies, the present work uses the NDVI to analyze the spatiotemporal variation in NDVI-derived vegetation index in Kunming City from 2000 to 2020. The objectives of this study are to (1) quantitatively identify the temporal trends and spatial patterns of NDVI-derived vegetation index over the past two decades, (2) reveal the relationships between vegetation dynamics and both climatic and socioeconomic factors; (3) evaluate the relative contributions of natural and socioeconomic factors to vegetation changes under the context of Kunming's rapid urban development.

2. Materials and Methods

2.1. Study Area

Kunming (102°23'–103°40' E, 24°23'–26°33' N) has a subtropical plateau mountain monsoon climate, shaped by the influence of the warm and humid air currents from the Indian Ocean. As the capital city of Yunnan Province, Kunming is actively fostering the agglomerated development of emerging industries such as green food, biomedicine, electronic information, new energy, and new materials, and has largely established a modern industrial system supported by modern agriculture, advanced manufacturing, and led by modern services. In recent years, Kunming's economy has maintained steady growth, with the tertiary sector playing a significant driving role and the private economy demonstrating increasing vitality. Key industrial chains and development zones have jointly contributed to the continuous enhancement of industrial cluster competitiveness. The city experiences neither severe winters nor extreme summer heat, maintaining a spring-like climate throughout the year. The annual mean temperature is approximately 15 °C, with an average of 2200 h of sunshine, a frost-free period exceeding eight months, and mean annual precipitation of about 1000 mm.

Geographically, Kunming is situated on the Yunnan-Guizhou Plateau, where most areas range in elevation from 1500 to 2800 m. The city's highest point is Mazongling Peak of the Gongwang Mountains, located between Dongchuan District and Luquan County, at an elevation of 4247.7 m. The lowest point lies at the confluence of the Jinsha River and Xiaojiangkou, at only 695 m above sea level. Kunming's urban center is positioned within the Dianchi Basin, with an average elevation of 1891 m.

Benefiting from its distinctive geographical and climatic conditions, Kunming supports exceptionally rich plant resources and diverse vegetation types. The main vegetation communities include subtropical evergreen broad-leaved forests, coniferous-broadleaved mixed forests, temperate coniferous forests, alpine shrublands, and meadows, all displaying a characteristic vertical zonal distribution. Representative taxa include species from the Fagaceae, Theaceae, and Lauraceae families. The city is especially abundant in seed plant resources, hosting 67% of the seed plant families found in China and more than 400 traditional flower varieties. Kunming is also rich in faunal diversity, with 61 species of nationally protected animals and over 500 vertebrate species recorded [11].

2.2. Data Sources and Statistical Analysis

The NDVI is widely recognized as an optimal indicator for assessing plant growth status. This study used MOD13Q1 data with a spatial resolution of 250 m (<https://ladsweb.modaps.eosdis.nasa.gov>, accessed on 26 March 2024), obtained from the GEE platform.

The MODIS NDVI products (MOD13Q1) already include atmospheric correction and cloud masking. Pixel-level quality control (QC) layers were used to remove low-quality or contaminated observations. Annual NDVI/FVC values were generated using a maximum value compositing strategy to minimize cloud and atmospheric interference. We selected MODIS NDVI (250 m resolution) because it provides a long-term and high temporal frequency dataset suitable for analyzing vegetation dynamics over a 20-year period. The 250 m spatial resolution is sufficient to capture regional vegetation patterns in Kunming's urban-mountain transition zones and has been widely used in similar long-term vegetation monitoring studies [12,13]. Following preprocessing steps such as mosaicking and clipping, annual mean NDVI values for Kunming from 2000 to 2020 were extracted. On this basis, the pixel dichotomy model was applied to calculate the fractional vegetation coverage (FVC). In our study, the NDVI reflects vegetation greenness and canopy vigor, whereas FVC quantitatively expresses the proportion of vegetation within a pixel. By deriving FVC from NDVI, we reduce the influence of soil background and vegetation type differences, allowing FVC to more accurately represent spatial variations in vegetation cover. To avoid confusion between greenness change and areal expansion, we derived FVC from NDVI using the pixel dichotomy model. NDVI was first analyzed at the pixel level, and then converted to FVC to quantitatively represent vegetation cover proportion per pixel. This allows distinguishing whether increases in vegetation were due to enhanced vegetation greenness within existing vegetated areas or due to the spatial expansion of vegetated surfaces. Therefore, while NDVI trends reflect vegetation vigor, FVC trends reflect changes in the areal extent of vegetation cover. The model is expressed as:

$$FVC = \frac{(NDVI - NDVI_{soil})}{(NDVI_{veg} - NDVI_{soil})} \quad (1)$$

where FVC represents the fractional vegetation coverage, $NDVI_{soil}$ is the NDVI value for bare soil pixels (completely soil-covered), and $NDVI_{veg}$ is the NDVI value for pure vegetation pixels (completely vegetation-covered). To ensure comparability across years, $NDVI_{soil}$ and $NDVI_{veg}$ were derived from the long-term NDVI dataset and kept constant over the entire study period. Statistical extraction of NDVI values was conducted using ENVI (version 5.3). The NDVI value corresponding to the 5% percentile of the cumulative probability distribution was defined as the bare-soil reference ($NDVI_{soil}$), whereas the 95% percentile was defined as the full vegetation reference ($NDVI_{veg}$). This percentile-based scaling approach has been widely used for vegetation cover retrieval in heterogeneous landscapes [14].

The calculated FVC values ranged from 0 and 1 and were classified into five equal interval categories: low (FVC: 0–0.2), low–medium (FVC: 0.2–0.4), medium (FVC: 0.4–0.6), medium–high (FVC: 0.6–0.8), and high vegetation coverage (FVC: 0.8–1) [15]. To quantify long-term changes in vegetation cover from 2000 to 2020, a pixel-based linear trend analysis was applied to annual FVC raster data. For each pixel, a temporal linear regression model was constructed to obtain the slope value, where a positive slope indicates improvement and a negative slope indicates degradation. The slope was calculated as:

$$\text{Slope} = \frac{n * \sum_{i=1}^n i * f_{vi} - \sum_{i=1}^n i \sum_{i=1}^n f_{vi}}{n * \sum_{i=1}^n i^2 - (\sum_{i=1}^n i)^2} \quad (2)$$

where slope represents the vegetation trend, n is the number of years, and f_{vi} is the vegetation cover in year i . To classify the slope values into improvement, stability, and degradation categories, we applied the Jenks natural breaks method, which optimizes grouping by minimizing within-class variance while maximizing between-class variance [16]. This approach has been widely used in ecological and land use studies to identify continuous

spatial gradients and vegetation trend patterns in a statistically robust manner [17,18]. Specifically, -0.072 to -0.021 indicates significant degradation, -0.021 to -0.007 moderate degradation, -0.007 to 0.005 stable conditions, 0.005 to 0.016 moderate improvement, and 0.016 to 0.063 significant improvement.

Temperature and precipitation data were obtained from the ERA5 Monthly Aggregates dataset of the European Centre for Medium-Range Weather Forecasts (ECMWF) through the GEE platform. ERA5, the fifth-generation ECMWF global atmospheric reanalysis, integrates model outputs with worldwide observations to produce a consistent global dataset. The ERA5 Monthly Aggregates product provides monthly mean values for seven climate parameters: 2 m air temperature, 2 m dew point temperature, total precipitation, mean sea-level pressure, surface pressure, a 20 m u-wind component, and a 10 m v-wind component. For this study, the 2 m air temperature and total precipitation variables were retrieved and used to calculate Kunming's annual mean temperature and annual total precipitation from 2000 to 2020. County-level gross domestic product (GDP) data for 2000–2020 were obtained from the Resource and Environment Science and Data Center of the Chinese Academy of Sciences (<http://www.resdc.cn>, accessed on 26 March 2024). The GDP data were included to characterize the background of Kunming's rapid urban development rather than to quantify causal effects on vegetation. NDVI-derived vegetation index values were aggregated to the same county scale to allow spatial correspondence analysis between economic development and vegetation patterns. The correlation coefficients and significance levels between FVC and the driving factors from 2000 to 2020 were calculated using MATLAB version R2023a, and the spatial visualization of the results was performed in ArcGIS version 10.7.

3. Results

3.1. Spatial Distribution Characteristics of NDVI-Derived Vegetation Index in Kunming

The spatial distribution of average NDVI-derived vegetation index in Kunming from 2000 to 2020 was relatively high in the northwestern, western, and southwestern regions of the city. In contrast, lower NDVI-derived vegetation index was observed in the main urban area of Kunming, the urban area of Anning City, the northern part of Shilin County, and the central-northern region of Dongchuan District. Areas with low NDVI-derived vegetation index (FVC: <0.2) accounted for 10.5% of the total area. Medium-low coverage (FVC: 0.2 – 0.4) represented 15.6% of the total area and was primarily distributed in the suburban zones of Kunming, the central area of Anning City, Yiliang County, the basin areas of Shilin County, most of Songming County, and the central part of Xundian County. Regions with medium coverage (FVC: 0.4 – 0.6) made up 24.4% of the total area. These zones were largely adjacent to areas with medium-low coverage, mainly distributed around the periphery of the regions with an FVC of 0.2 – 0.4 . Areas with medium-high coverage (FVC: 0.6 – 0.8) accounted for 24.2% of Kunming's area, with a broad distribution across Fumin County, Wuhua District, the northern part of Panlong District (central Kunming), and portions of Dongchuan District and Xundian County. High NDVI-derived vegetation index (FVC: 0.8 – 1) comprised approximately 25% of the total area, concentrated in the northern part of Luquan County (northwestern Kunming), Fumin County (southwestern Kunming), Xishan District, Anning City, and parts of Jinning District.

Overall, the spatial distribution of NDVI-derived vegetation index in Kunming is characterized by higher values in the west than in the east, and higher values in mountainous regions compared with plain basins. The temporal trend over the past 21 years indicates a steady overall increase in NDVI-derived vegetation index. Between 2000 and 2010, the extent of low NDVI-derived vegetation index areas decreased, with particularly notable reductions in the central–northern part of Dongchuan District, the northern part of Luquan

County, and the northern part of Shilin County. In contrast, accelerated urbanization in the main urban area resulted in an expansion of low-coverage zones. During this period, the proportions of medium-low, medium, and medium-high vegetation coverage remained relatively stable without major shifts, while areas of high NDVI-derived vegetation index expanded slightly, primarily across central and western Luquan, Xishan District, Fumin County, and the western part of Anning City.

By 2020, the structure of the NDVI-derived vegetation index in Kunming had undergone substantial changes compared with that in 2010. Although the total extent of low NDVI-derived vegetation index remained relatively stable, its spatial distribution shifted markedly. Low-coverage areas in the central part of Xundian County, the northern part of Dongchuan District, and the northern part of Shilin County, decreased significantly, reflecting the effectiveness of ecological restoration initiatives. In contrast, low-coverage areas expanded considerably in Chenggong District and Songming County, largely due to urban expansion. Meanwhile, the extents of medium-low and medium NDVI-derived vegetation index continued to contract, whereas medium-high NDVI-derived vegetation index expanded substantially. The most pronounced increase occurred in high-vegetation-coverage areas, which were concentrated primarily in the central-northern part of Panlong District, Xishan District, the western part of Anning City, and the western region of Luquan County.

3.2. Temporal Distribution Characteristics of NDVI-Derived Vegetation Index in Kunming

As shown in Figure 1, the NDVI-derived vegetation index for the entire study area increased over 2000–2020, with interannual variability but a statistically significant long-term upward trend ($r = 0.404$, $p < 0.05$). From 2000 to 2002, the NDVI increased notably from 0.48 to 0.52. Between 2002 and 2020, NDVI values alternated between periods of increase and decline, but the long-term trend remained positive. The most pronounced growth occurred between 2012 and 2016, when the NDVI rose from 0.49 to 0.55. Across the 21-year span, the minimum NDVI value was 0.48 (in 2000), while the maximum value reached 0.55 (in 2019). Marked declines were recorded in 2010 and 2012, likely due to severe droughts triggered by substantially reduced rainfall in 2009 and 2011. Overall, Kunming's NDVI increased from 0.48 in 2000 to 0.55 in 2020, representing a total gain of 0.07. Given the bounded nature of NDVI (0–1), this magnitude of increase indicates a meaningful enhancement in vegetation condition at the regional scale.

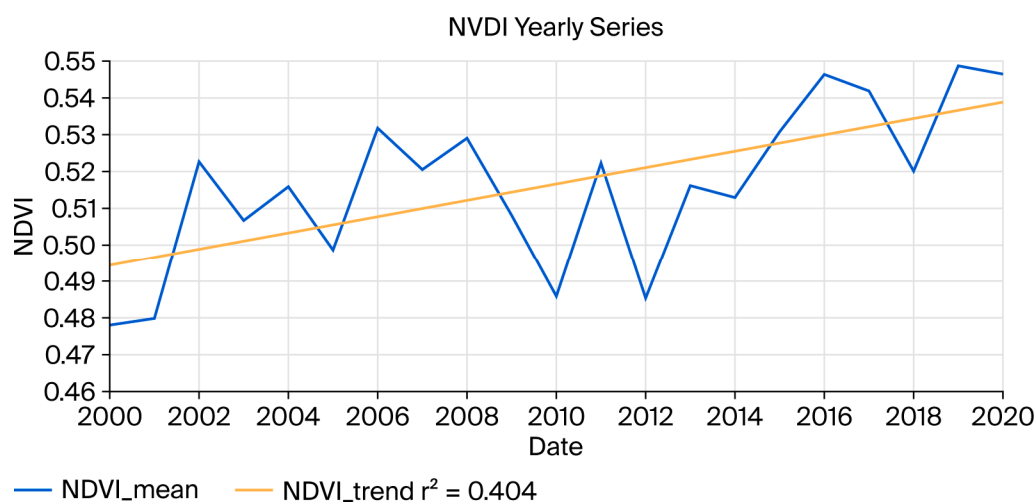


Figure 1. Interannual variation and long-term trend of the NDVI-derived vegetation index in Kunming (2000–2020).

From 2000 to 2020, NDVI-derived vegetation index in Kunming experienced notable structural shifts. Area with low NDVI-derived vegetation index (FVC: 0–0.2) remained essentially stable throughout the period. In contrast, areas with low–medium NDVI-derived vegetation index (FVC: 0.2–0.4) declined substantially, decreasing from 18% to 14% of the total area. Medium-coverage regions (FVC: 0.4–0.6) also contracted, with their proportion falling from 26% to 23%. Conversely, areas with medium–high coverage (FVC: 0.6–0.8) expanded from 23% to 26%, while the most pronounced increase occurred in high-coverage regions (FVC: 0.8–1), which grew from 19% to 26%. Taken together, these results indicate substantial overall improvement in NDVI-derived vegetation index across Kunming during the study period.

Over the 21-year period, changes in the proportional area of most NDVI-derived vegetation index classes in Kunming were relatively minor, except for high-coverage regions (FVC: 0.8–1), which increased by approximately 2%. However, the decade from 2010 to 2020 displayed the most pronounced shifts. During this period, the proportion of low-medium-coverage regions (FVC: 0.2–0.4) declined from 17% to 14%, while medium-coverage regions (FVC: 0.4–0.6) also showed a clear downward trend, decreasing from 26% to 23%. In contrast, regions with medium-high and high coverage expanded. Specifically, medium-high-coverage areas (FVC: 0.6–0.8) rose from 23% to 26%, and high-coverage areas (FVC: 0.8–1) increased substantially from 19% to 26%. These results confirm that NDVI-derived vegetation index in Kunming followed a steady upward trajectory, particularly in the most recent decade.

As shown in Figure 2, areas with essentially unchanged NDVI-derived vegetation index were the most extensive, covering 10,633 km² and accounting for 52.51% of Kunming's total area. Regions exhibiting vegetation degradation occupied 10.28% of the total area, including 480.98 km² classified as significantly degraded (2.37%) and 1600.93 km² as moderately degraded (7.91%). In contrast, areas with improved NDVI-derived vegetation index represented 37.21% of the total area, comprising 5440.04 km² of moderately improved regions (26.86%) and 2095.30 km² of significantly improved regions (10.35%). In terms of spatial distribution, NDVI-derived vegetation index in Kunming exhibited an overall upward trend. Areas with significant improvement were primarily concentrated in parts of Xundian County (northeastern Kunming), sections of Dongchuan District, the northern portion of Luquan County, and the northern border region between Yiliang County and Shilin County. Significantly degraded regions were primarily distributed along the corridor extending from Kunming's main urban area to the urban center of Songming County (including the airport zone). Additional degradation hotspots were observed in Chenggong District, the southwestern margin of Dianchi Lake bordering Anning City and Jinning District, and the main urban areas of Yiliang County and Shilin County.

Overall, between 2000 and 2020, regions with significantly improved NDVI-derived vegetation index in Kunming were concentrated in the eastern part of the city, whereas significantly degraded regions were mainly distributed in Kunming's central urban area and the urban centers of several surrounding districts and counties. Notably, the three northern counties, Luquan, Dongchuan, and Xundian, were dominated by vegetation improvement, while the remaining 11 southern districts and counties displayed a mixed pattern of both improvement and degradation.

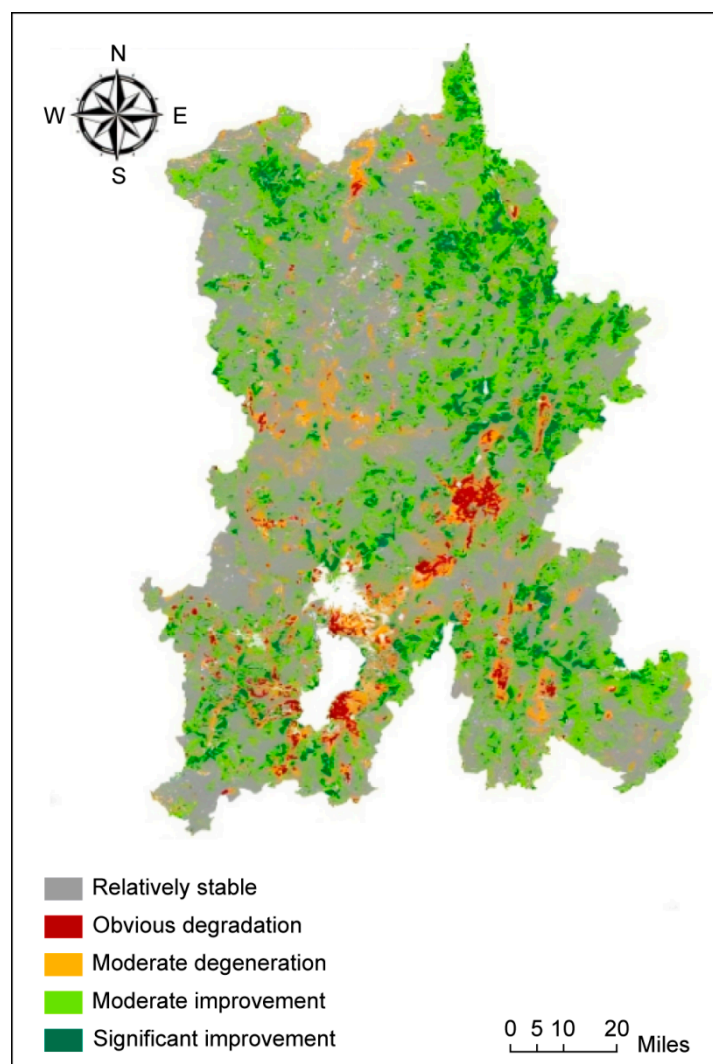


Figure 2. Temporal trend of the NDVI-derived vegetation index in Kunming from 2000 to 2020.

3.3. Impact of Temperature on NDVI-Derived Vegetation Index in Kunming

From 2000 to 2020, both temperature and the NDVI in Kunming exhibited fluctuating upward trends, although their interannual variation patterns occasionally diverged (Figure 3). The annual mean temperature decreased in 2004, 2006–2008, 2011, and 2014–2018, whereas NDVI increased to varying degrees in the same years. These temporal trends indicate an association rather than a strictly synchronous pattern between NDVI-derived vegetation index and temperature (NDVI slope: -0.85 to -0.3 , and 0.3 to 0.82). Correlation analysis was performed between the NDVI and temperature from 2000 to 2020, with the results shown in Figure 4.

The spatial distribution of the correlation between NDVI-derived vegetation index and temperature in Kunming from 2000 to 2020 is shown in Figure 5. Areas where NDVI-derived vegetation index and temperature exhibited a positive correlation covered $11,230 \text{ km}^2$, representing 53.3% of Kunming's total area. Of this, 3927.83 km^2 (18.6% of the total area) showed a significant positive correlation, mainly distributed across the northern and western parts of Luquan County, the border region between Luquan, Dongchuan, and Xundian, and much of Xishan District, Anning City, and Jinning District in southwestern Kunming. The remaining 7302.17 km^2 (34.7% of the total area) displayed an insignificant positive correlation, concentrated primarily in the southeastern part of Dongchuan District,

the central and southern areas of Xundian, the central portion of Panlong District, and the central parts of Yiliang County and Shilin County.

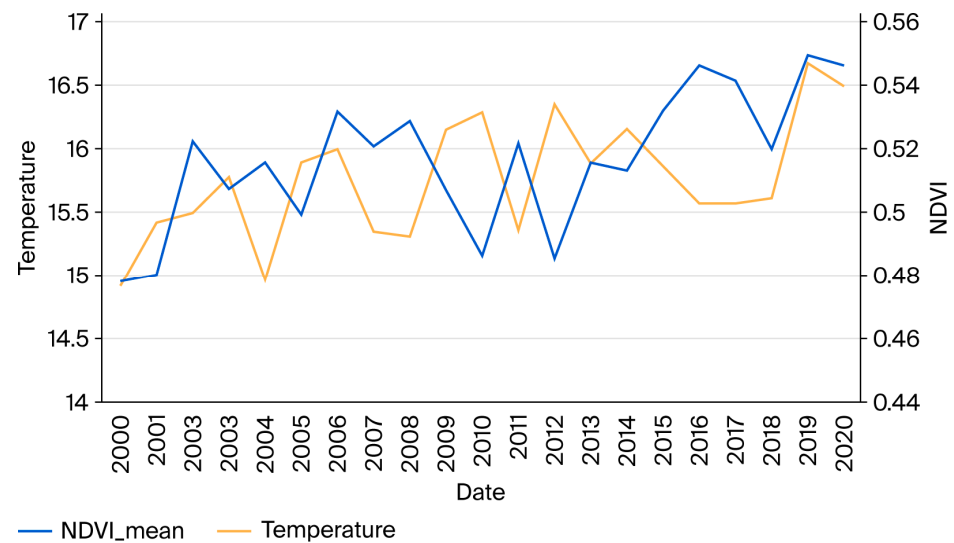


Figure 3. Temporal variations in temperature and the NDVI-derived vegetation index in Kunming (2000–2020).

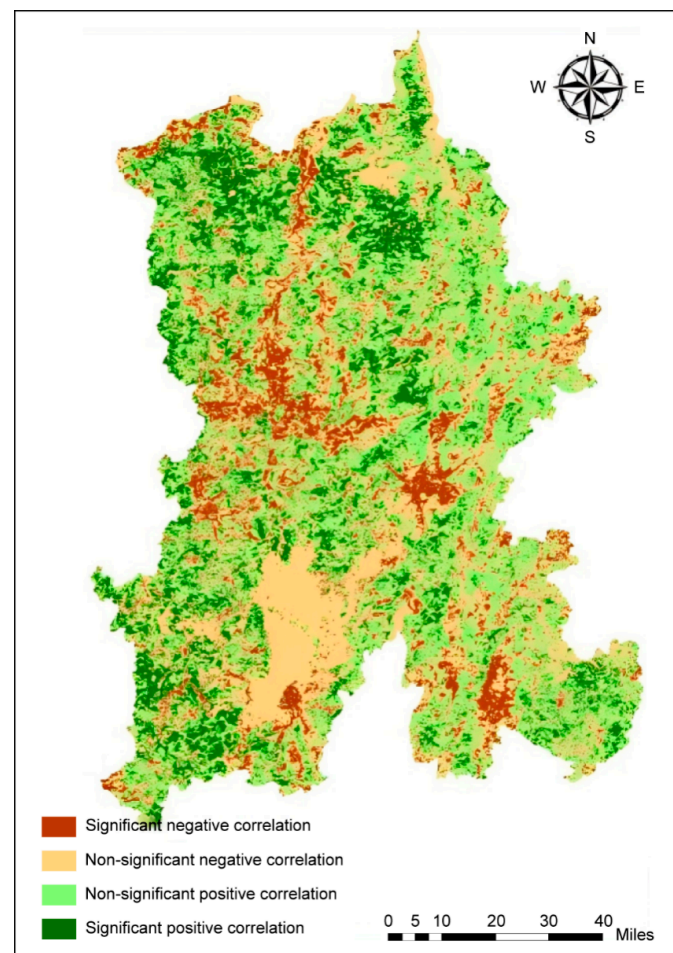


Figure 4. Spatial correlation between temperature and the NDVI-derived vegetation index in Kunming. Note: Significant negative correlation (-0.85 to -0.3), insignificant negative correlation (-0.3 to 0), insignificant positive correlation (0 to 0.3), and significant positive correlation (0.3 to 0.82).

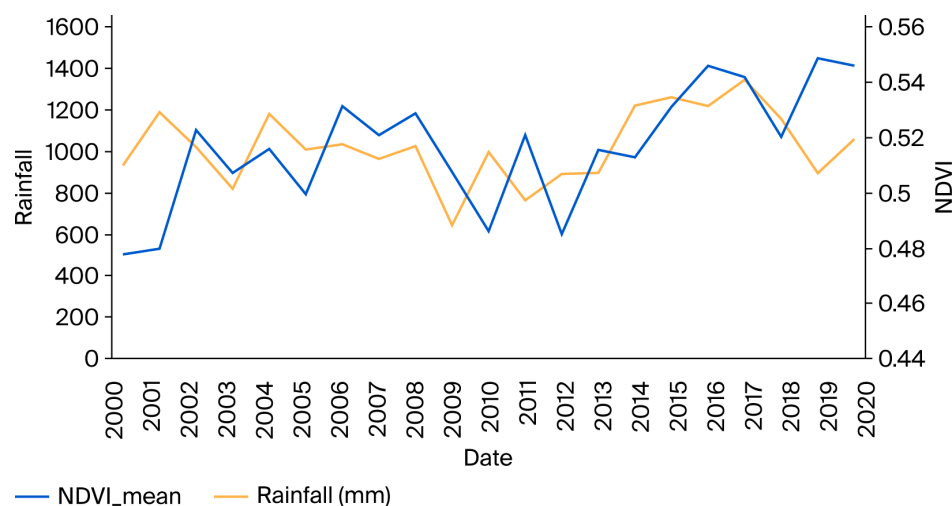


Figure 5. Temporal variations in annual precipitation and the NDVI-derived vegetation index in Kunming (2000–2020).

Areas where NDVI-derived vegetation index and temperature were negatively correlated covered 9834.8 km², accounting for 46.7% of Kunming's total area. Within this, significantly negative correlations were relatively limited, totaling 2459.81 km² (11.7% of the total area). These zones were primarily concentrated in the lower reaches of the Pudu River (where it enters the Jinsha River) in northern Luquan County, the border region between Luquan and Fumin Counties, parts of Jincheng in Jinning District, the basin surrounding the county seat of Songming, and the basin areas of Goujie Town in Yiliang County and the county seat of Shilin County. The strong negative correlation areas were mainly concentrated in Songming, Jinning, Yiliang, and Shilin. Areas with an insignificant negative correlation covered 7374.99 km², or 35% of the total area. These were widely distributed, often occurring as transitional zones between significantly negative and insignificantly positive correlation regions. More concentrated distributions were observed in Kunming's main urban area, along the corridor from the airport to Songming, and in the main urban centers of Chenggong District, Anning City, and Jinning District.

3.4. Impact of Precipitation on NDVI-Derived Vegetation Index in Kunming

As shown in Figure 5, the precipitation and NDVI change curves in Kunming from 2000 to 2020 exhibited broadly similar trends. From 2000 to 2011, precipitation displayed pronounced interannual fluctuations, and NDVI-derived vegetation index varied accordingly. However, sharp increases or decreases in precipitation did not immediately translate into equivalent changes in NDVI-derived vegetation index; rather, the effects typically lagged by about one year. For example, precipitation rose markedly in 2001 and 2010, but the NDVI did not increase significantly until 2002 and 2011, respectively. Likewise, precipitation dropped sharply in 2009 and 2011, reaching the lowest levels of the 21-year period, and NDVI-derived vegetation index correspondingly declined in 2010 and 2012.

The spatial correlation results between NDVI-derived vegetation index and precipitation in Kunming from 2000 to 2020 are shown in Figure 6. Overall, NDVI-derived vegetation index was predominantly positively correlated with precipitation. Regions with a positive correlation covered 11,135.09 km², accounting for 53% of Kunming's total area. Among these, 4148.45 km² (19.7%) showed a significant positive correlation, primarily distributed along the Jinsha River Basin in northern Kunming, the Pudu River Basin in Luquan County and Fumin County, the Xiaojiang Basin in Dongchuan District, the northern and northeastern parts of Xundian, and the central and southwestern regions of Yiliang County. These areas were relatively concentrated, especially in river valleys and dam

regions. The remaining 6986.64 km² (33.3%) exhibited an insignificant positive correlation, generally surrounding the significantly correlated zones and mainly distributed in Luquan County, Fumin County, Dongchuan District, Xundian County, Yiliang County, and Shilin County. Overall, regions with positive correlations between NDVI-derived vegetation index and precipitation were concentrated in northern Kunming and in the Yiliang and Shilin areas of the southeast.

Regions where NDVI-derived vegetation index was negatively correlated with precipitation covered 9881.32 km², accounting for 47% of Kunming's total area. Within this, significantly negative correlations were limited, occupying 1750.47 km² (8.3% of the total area). These areas formed a relatively small proportion overall and were scattered, though some clusters occurred in the northern part of Panlong District, the central area of Xishan District, the western part of Anning City, and the southwestern part of Jinning District. Areas with an insignificant negative correlation were more extensive, covering 8130.85 km² (38.7% of the total area). These zones were primarily interspersed between regions of significant negative and insignificant positive correlation, with relatively concentrated distributions in Kunming's main urban area, the airport and its surrounding areas. Overall, a negative correlation between NDVI-derived vegetation index and precipitation were mainly concentrated in central and southwestern Kunming and its surrounding districts.

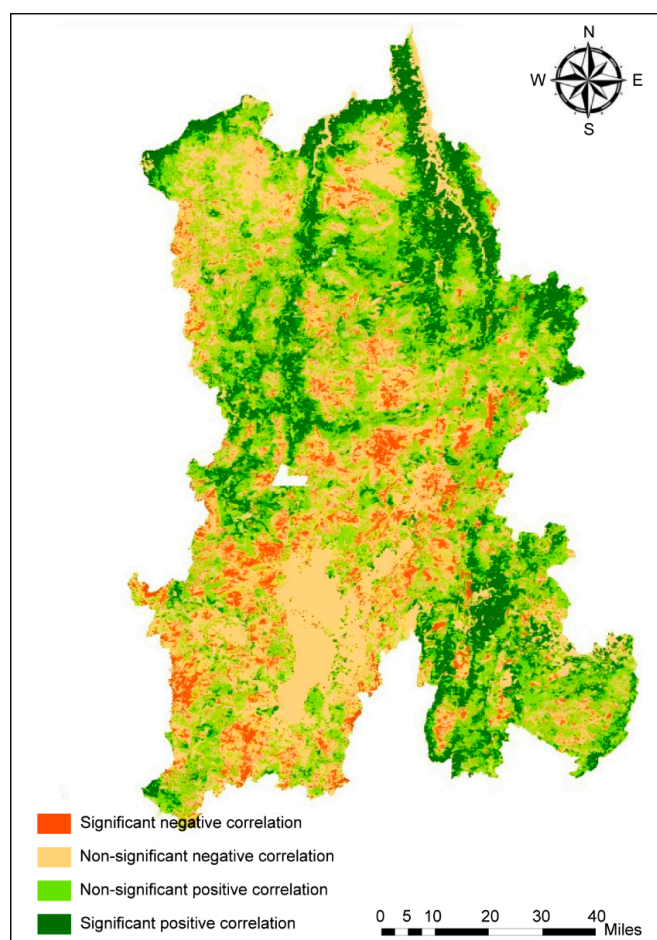


Figure 6. Spatial correlation between precipitation and the NDVI-derived vegetation index in Kunming. Note: Significant negative correlation (−0.85 to −0.3), insignificant negative correlation (−0.3 to 0), insignificant positive correlation (0 to 0.3), and significant positive correlation (0.3 to 0.82).

3.5. Trend of GDP Change in Kunming from 2000 to 2020

As shown in Figure 7, which illustrates GDP changes in Kunming from 2000 to 2020, the city experienced remarkable economic growth during the study period. GDP increased from CNY 63.61 billion in 2000 to CNY 673.38 billion in 2020, representing a more than tenfold expansion over 21 years. Between 2003 and 2015, Kunming's annual GDP growth rate consistently exceeded 10%, peaking at 19.18% in 2012.

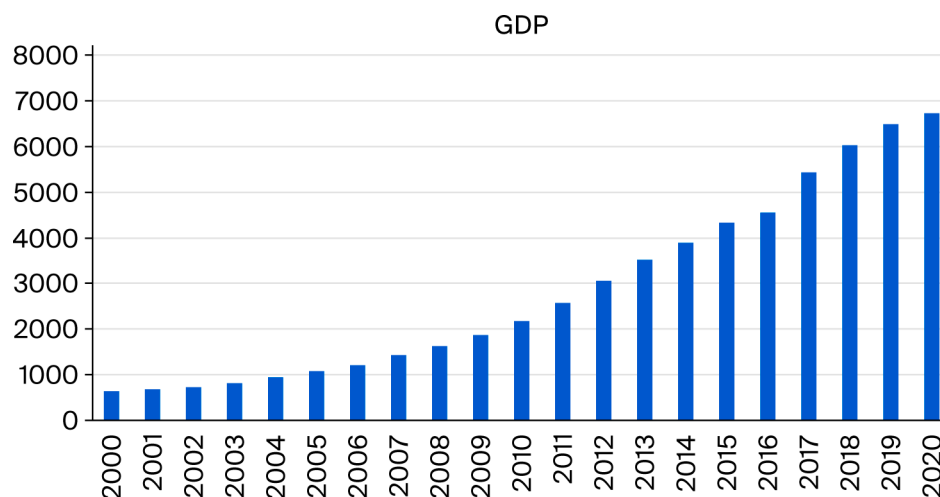


Figure 7. Annual GDP of Kunming from 2000 to 2020.

The spatial distribution of Kunming's GDP in 2019, with GDP values exceeding CNY 500 billion were concentrated in the city's five urban districts: Xishan, Panlong, Guandu, Wuhua, and Chenggong. However, these economically developed districts corresponded to areas of relatively low NDVI-derived vegetation index. The only region with a GDP between CNY 300 and 500 billion was Anning City, where the GDP of its main urban area alone exceeded CNY 500 billion. Similarly, NDVI-derived vegetation index in the main urban area of Anning and its surrounding regions was relatively low.

4. Discussion

Kunming is situated in central Yunnan and belongs to the subtropical monsoon climate zone, characterized by abundant vegetation resources. Changes in NDVI-derived vegetation index are influenced by multiple factors, among which precipitation and temperature have been widely recognized as key drivers [19]. In recent years, however, rapid socioeconomic development and intensified human activities have led to continuous changes in land use, exerting a profound impact on vegetation dynamics. Consequently, both climatic and anthropogenic factors have become critical determinants of NDVI-derived vegetation index in the region [20]. In 2016, NDVI increased despite relatively stable temperature conditions, which likely reflects vegetation recovery following earlier drought stress rather than a temperature-driven response alone. This indicates that vegetation dynamics during this period were influenced not only by climatic factors but also by continued ecological restoration, afforestation, and land management activities.

Since 2000, NDVI-derived vegetation index in Kunming has remained generally stable. Areas with high coverage have been concentrated in the northern and western parts of the city, while low coverage has been primarily confined to the main urban area. Regions of significant improvement were mainly located in eastern Kunming [9], which is largely consistent with the results of this study on spatiotemporal vegetation changes. From 2000 to 2020, the NDVI-derived vegetation index in Kunming showed a fluctuating upward trend. The annual average NDVI increased from 0.48 in 2000 to 0.55 in 2020, with the maximum

annual average NDVI reaching 0.55 in 2019. Notable declines were observed in 2010 and 2012, likely associated with severe droughts following substantial reductions in rainfall in 2009 and 2011. Despite these short-term anomalies, NDVI-derived vegetation index in Kunming demonstrated a clear long-term trend of improvement over the 21-year period.

Over the past 21 years, temperature in Kunming has shown a significant upward trend, exhibiting a measurable correlation with NDVI-derived vegetation index. Areas with a positive correlation accounted for 53.3% of the total area, including 18.6% with a significant positive correlation and 34.7% with an insignificant positive correlation. In contrast, 35% of the area showed an insignificant negative correlation, while 18.6% displayed a significant negative correlation. From 2000 to 2020, NDVI-derived vegetation index changes in Kunming were more strongly associated with precipitation variability. Regions with a positive correlation between NDVI-derived vegetation index and precipitation covered 11,135.09 km², or 53% of the total area. However, interannual differences were evident. In particular, precipitation exerted a lagged effect on NDVI-derived vegetation index, with changes typically reflected after one year. Despite this delay, precipitation and NDVI-derived vegetation index remained generally consistent in their trends, confirming that precipitation changes play a critical role in shaping vegetation dynamics in Kunming [21]. In addition, the areas showing strong negative temperature-NDVI-derived vegetation index correlations, such as Songming, Jinning, Yiliang and Shilin, coincide with zones experiencing intensive human activities and extensive agricultural land use, indicating that anthropogenic disturbance can partially offset climatic benefits and weaken vegetation greening in these regions.

During the 21-year period, Kunming's GDP increased from CNY 63.613 billion in 2000 to CNY 673.379 billion in 2020, representing a tenfold increase. A spatial comparison with NDVI-derived vegetation index maps from the same period shows that areas with higher GDP values generally corresponded to lower NDVI-derived vegetation index, whereas regions with lower GDP were associated with higher NDVI-derived vegetation index. This contrasting spatial pattern indicates that rapid economic development and vegetation improvement did not occur evenly across space; rather, vegetation gains were mainly distributed outside the main urban area. A comparison between the 2019 GDP spatial distribution map and the NDVI-derived vegetation index distribution map further confirms this spatial mismatch within the five major urban districts. This pattern reflects the typical landscape characteristics of rapidly urbanizing areas, where the concentration of impervious surfaces and intensive land use in economic centers correspond to relatively low vegetation coverage. Here, the observed relationship reflects spatial co-occurrence rather than causation, and the mechanisms underpinning this pattern warrant further investigation.

In this study, we identified clear temporal trends in vegetation dynamics and their climatic responses in Kunming. However, when interpreting long-term FVC patterns derived from NDVI, certain uncertainties should be acknowledged. NDVI retrievals may be influenced by sensor noise, soil background reflectance, and atmospheric conditions such as cloud cover and aerosol loading, which are particularly relevant in plateau and mountainous regions like Kunming [22]. Additionally, vegetation types differ in their spectral responses, meaning that the same NDVI value may correspond to different levels of vegetation cover in broadleaf forests, coniferous forests, and grasslands. More importantly, the NDVI-FVC relationship is not strictly linear; NDVI tends to saturate in areas with dense vegetation, which may lead to underestimation of FVC and weaken the apparent magnitude of vegetation improvement [23]. Furthermore, in densely built-up and peri-urban areas, MODIS pixels may represent a mixture of vegetation and non-vegetation surfaces, which can introduce uncertainty into NDVI/FVC estimates. Therefore, while the observed trends in vegetation cover are robust at the regional scale, the results should be

interpreted with caution at the fine spatial scale, particularly in high-coverage forested areas. These uncertainties highlight the need for future work to integrate higher-resolution remote sensing data (e.g., Sentinel or Landsat) or multi-index vegetation parameters to further refine the spatial detail of vegetation change assessments.

Furthermore, the lack of long-term in situ vegetation monitoring in the study area adds uncertainty to the correspondence between satellite-inferred vegetation dynamics and actual on-ground processes. In addition, although ERA5 reanalysis data provide consistent long-term climate information, their coarse spatial resolution may be inadequate for resolving micro-climatic variability across heterogeneous urban–mountain environments. While these limitations do not alter the major regional-scale conclusions of this study, they underscore the need for future work to integrate higher-resolution climate data and ground-based measurements to enhance the precision of vegetation–climate interaction assessments.

5. Conclusions

This study integrates MODIS remote sensing data and ERA5 climate reanalysis data to quantify the spatiotemporal variations in the NDVI-derived vegetation index in Kunming from 2000 to 2020. The results show that the NDVI-derived vegetation index exhibited a fluctuating yet statistically significant long-term upward trend, forming a distinct spatial pattern characterized by high vegetation cover in the west and peripheral areas and low cover in the eastern and main urban area zones. Areas of vegetation improvement (37.2% of the total area) substantially exceeded areas of degradation (10.3%). Climatic analyses indicate that precipitation was the primary natural factor regulating interannual vegetation dynamics, while the effect of temperature displayed strong spatial heterogeneity. The comparison between GDP and vegetation maps further revealed a spatial mismatch in which economically concentrated urban districts corresponded to relatively low vegetation cover, reflecting the landscape characteristics of rapid urbanization rather than a direct causal effect. Overall, this work provides an improved understanding of the long-term vegetation dynamics of Kunming and offers a scientific reference for strengthening ecological resilience and promoting sustainable urban development in rapidly urbanizing regions.

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