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Spatiotemporal vegetation dynamics in South Asia (2001-2023): roles of climate and anthropogenic activities

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Abstract

Vegetation maintains ecological balance, supports biodiversity, and influences regional climate patterns. This study evaluated vegetation changes across South Asia (2001–2023) using NDVI data from MODIS satellites. Climatic and anthropogenic factors influencing vegetation were examined through the Mann–Kendall trend test, Sen's slope estimator, residual trend analysis, and Hurst exponent analysis. Results indicated a widespread greening trend driven by afforestation, improved irrigation, and sustainable land management. Vegetation decline (16.9% from residual trend analysis) was observed in urbanized and deforested areas. Precipitation emerged as the primary climatic driver, with approximately 70.5% of vegetated regions showing positive correlations with rainfall. Temperature effects were spatially varied, extending growing seasons in high-altitude regions such as the Hindu Kush and Himalayas, while contributing to vegetation stress in arid zones. Residual trend analysis highlighted human influence, with 83.1% of vegetated areas showing positive trends. Hurst exponent analysis predicted persistent greening (96.5%), emphasizing the importance of climate-resilient land management policies, targeted afforestation, and sustainable agricultural practices to promote ecological resilience.

Keypoints

- Vegetation in South Asia increased from 2001 to 2023 due to afforestation, irrigation, and sustainable land management efforts.
- Precipitation mainly drives vegetation growth, while temperature impacts vary, benefiting highlands but stressing arid regions.
- Human activities boosted vegetation in 83.1% of areas, but 16.9% faced losses due to urbanization, deforestation, and land degradation.

Plain Language Summary

This study explores changes in vegetation across South Asia from 2001 to 2023, using satellite data to understand the impacts of climate and human activities. The results revealed that vegetation is increasing in many areas due to afforestation, improved irrigation, and sustainable land management practices. However, vegetation loss is prominent in urbanizing and deforested regions. Rainfall was found to be the most important climatic factor for vegetation health, with most regions showing a strong positive link between rainfall and vegetation growth. Temperature effects varied; increasing temperature extended growing seasons in high-altitude regions but stressed plants in arid areas.

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The study also highlights human efforts, such as afforestation and land management, which have improved vegetation in many areas. Despite this progress, some regions face long-term vegetation decline, emphasizing the need for targeted conservation policies to ensure ecological resilience across South Asia.

Introduction

Vegetation is an important component of the Earth's ecosystems, serving as an indicator of ecological health, playing a major role in carbon sequestration, and influencing climate patterns (Newbold et al. 2015). It also significantly supports the livelihoods of local communities. Temperature and precipitation are the primary climatic drivers affecting the distribution and growth of vegetation and are, in turn, influenced by vegetation itself (Shrestha et al. 2024). Anthropogenic activities, such as urbanization, deforestation, and agricultural practices, also significantly affect vegetation dynamics alongside climatic influences (Guo et al. 2021; Shrestha et al. 2024).

In regions where water availability is limited, precipitation largely governs vegetation growth, whereas temperature predominantly determines growing seasons and vegetation health, especially in temperature-sensitive ecosystems (Wang et al. 2024). Climatic factors, combined with soil moisture, wind, and human activities, give rise to complex and region-specific patterns of vegetation change (Shrestha et al. 2024). Rising temperatures can extend the growing seasons in colder climates but cause vegetation stress in arid regions (Piao et al. 2014). Besides climate, urbanization, overgrazing, deforestation, and intensive agriculture often lead to vegetation degradation. In contrast, actions such as afforestation, reforestation, and sustainable land management encourage vegetation growth. Initiatives like China's Grain for Green Program and Nepal's community-based forestry have shown how effective human interventions can reverse ecological degradation (Cadavid Restrepo et al. 2017; Pathak et al. 2017). Understanding vegetation dynamics and their driving factors is essential for anticipating ecosystem changes, developing sustainable forest management strategies, and improving resilience to climate change.

South Asia is home to 24% of the global population, a figure projected to reach 41% in 2050 (Bloom & Rosenberg 2011), while covering only 3% of the Earth's land surface (Ali et al. 2020a). Meeting the housing and food demands of such a large population has led to extensive deforestation, as forests have been converted into agricultural and urban areas. These changes have intensified the region's vulnerability to ecological imbalance. Nevertheless, South Asia is ecologically diverse, with the highest mountain ranges (e.g., the Himalayas, the Karakoram, and the Hindukush) in the north and northwest, a vast Indo-Gangetic plain spanning over 700,000 square kilometers, and the Indian Ocean to the south. Vegetation cover is, therefore, crucial for maintaining ecological stability and sustaining natural resources in this region.

The Normalized Difference Vegetation Index (NDVI) has become a widely used metric for studying vegetation dynamics across temporal and spatial scales, particularly to evaluate how vegetation responds to climatic variations and human impacts (Kang et al. 2017; Guo et al. 2021; He et al. 2021; Gao et al. 2022; Prăvălie et al. 2022; Shrestha et al. 2024). NDVI quantifies vegetation greenness and its spatial distribution (Banerjee et al. 2020), identifying areas of sparse or dense vegetation. Thus, NDVI is highly valuable in analyzing vegetation characteristics across landscapes (Mehmood et al. 2024).

Researchers commonly apply the Mann–Kendall trend test to identify significant temporal trends in vegetation, while Sen's slope helps quantify the magnitude of these trends. NDVI data derived from remote sensing has been widely used to explore relationships between climatic factors and vegetation dynamics, thereby identifying dominant drivers of regional vegetation change (Zhe and Zhang 2021; Zhang et al. 2022; Han et al. 2023; Mehmood et al. 2024). Ghaderpour et al. (2023) observed a stronger annual correlation between NDVI and Land Surface Temperature (LST) compared to precipitation when assessing these climate relationships. Similarly, Prăvălie et al. (2022) stated that changes in forest productivity are primarily driven by climate, particularly warming trends accompanied by increased evapotranspiration and reduced precipitation. Such shifts clearly indicate significant climate-driven impacts on vegetation health.

Residual trend analysis is a useful approach for isolating human impact from climatic factors, providing insights into how human activities specifically affect vegetation changes (Wessels et al. 2007). Additionally, Hurst exponent analysis, coupled with NDVI trends, is valuable for predicting future vegetation trajectories by assessing the persistence of observed trends over time (Qu et al. 2020). For instance, consistent greening trends suggest sustainable vegetation growth, whereas browning trends indicate potential degradation, often linked to urbanization or overexploitation (Shrestha et al. 2024).

Given this context, this study addresses the following research questions:

(1) *How have vegetation dynamics varied spatially and temporally across South Asia over the past two decades?*
(2) *What is the relative influence of climatic factors, specifically precipitation and temperature, on vegetation growth in different regions of South Asia?*
(3) *Can trends observed in vegetation dynamics predict future ecological sustainability and resilience across different regions in South Asia?*

The primary objectives of this study are to assess the spatiotemporal patterns and variability of vegetation across South Asia from 2001 to 2023 using MODIS-derived NDVI. The study identifies key climatic drivers, specifically precipitation and temperature, influencing vegetation trends across diverse climatic regions. It also evaluates human impacts on vegetation using residual trend analysis. Additionally, the research predicts the persistence of current vegetation trends through Hurst exponent analysis to understand future ecological sustainability. Finally, the study proposes practical recommendations for sustainable land management, climate-resilient agriculture, and ecological conservation based on observed vegetation dynamics.

Materials and methods

The study area

South Asia, the sub-region of Asia, includes Afghanistan, Bangladesh, Bhutan, India, Nepal, Pakistan, Sri Lanka, and the Maldives. It is bounded in the north by the Hindu Kush, Karakoram, and Himalayan Mountain ranges stretching from northwest to northeast. Major rivers such as the Indus, Ganges, and Brahmaputra originate from these mountains and flow into the extensive Indo-Gangetic Plain located immediately south. South Asia is home to approximately 25.29% of the global population, making it one of the most densely populated regions on Earth. Although the region contributes only 8% of global carbon emissions, it remains highly vulnerable to climate change impacts. Seasonal monsoon rainfall and temperature variations govern the vegetation growth, productivity, and distribution throughout South Asia, significantly influencing both natural ecosystems and agricultural landscapes.

Datasets

In this study, we used NDVI (MOD13A2) data having a spatial resolution of 1 km and a temporal resolution of 16 days, as well as LST (MOD11A2) data with an 8-day temporal and 1-km spatial resolution. These datasets were obtained from MODIS satellite imagery using the Google Earth Engine (GEE) platform, and annual mean values were calculated for the period 2001–2023. A scale factor of 0.0001 was applied to the NDVI images to normalize their values within the standard range of −1 to 1. Similarly, LST data were multiplied by a scale factor of 0.02 to convert the original data into Kelvin, after which 273.15 was subtracted to express LST values in degrees Celsius (°C). The mean temperature and precipitation data used in this analysis were retrieved from the ERA5 dataset using GEE. Additionally, potential evapotranspiration (PET) was derived using the Penman–Monteith equation with ERA5-derived climatic parameters, including minimum and maximum temperatures, dewpoint temperature, surface pressure, solar radiation, and wind components (u and v).

Mann–Kendall trend and Sen's slope estimator

To evaluate temporal trends and their significance in NDVI dynamics, the non-parametric Mann–Kendall trend test was applied. Trends were considered significant at a 95% confidence level. A Z-value greater than 1.96 indicated the existence of a significant increasing trend, while a value less than −1.96 indicated a significant decreasing trend. The values between −1.96 and 1.96 denote a non-significant trend. Sen's slope estimator was used to quantify the magnitude of these trends, where positive values indicate an increase in vegetation cover and negative values signify a decline.

Hurst exponent analysis

The Hurst exponent (H) is a statistical measure used in this research to predict future NDVI trends by quantifying whether vegetation patterns exhibit persistent, random, or anti-persistent behavior over time. First introduced by Hurst (1951), this approach helps forecast future vegetation trends, guiding ecological management decisions. In this study, the Rescaled Range (R/S) Analysis method outlined by Tong et al. (2018) was adopted to calculate the Hurst exponent, quantifying the scaling behavior of NDVI time series data. The Hurst exponent ranges between 0 and 1. Values below 0.5 indicate anti-persistence behavior, suggesting a potential reversal of current trends in the future. Values greater than 0.5 show persistent behavior, implying that the current vegetation trend will likely continue in the future (Hurst 1951; Xu et al. 2024).

Residual trend analysis

Residual trend analysis is a multi-step approach that is used to quantify the impact of anthropogenic activities on vegetation dynamics by isolating the effects of climatic factors. In this study, precipitation, mean temperature, potential evapotranspiration (PET), and land surface temperature (LST) were considered as independent variables, with NDVI data from 2001 to 2023 serving as the dependent variable. These climatic variables have direct relationship with vegetation stress and vigor, thereby affect vegetation growth in an area. A multiple linear regression model was applied to estimate NDVI based on these climatic predictors, as expressed by the following equation.

$$NDVI = \beta_0 + \beta_1(Prec) + \beta_2(MeanTemp) + \beta_3(PET) + \beta_4(LST) + \varepsilon \quad (1)$$

where NDVI is the dependent (response) variable, while precipitation, mean air temperature, PET, and LST are independent (predictor) variables that affect NDVI. In this model β_0 is the intercept, while $\beta_1, \beta_2, \beta_3$ and $\beta_4$are regression coefficients corresponding to precipitation, mean temperature, PET, and LST, respectively. The term ε represents the residual error. Based on the regression model, the mean annual NDVI was calculated in each pixel through the mentioned coefficients, and then the mean annual NDVI residual values were obtained from the difference between the actual NDVI and the model-predicted NDVI. This approach allows us to isolate the influence of human activities on NDVI from the influence of climatic factors. A positive residual trend indicates human-induced greening effects on vegetation, while a negative residual trend suggests human-induced degradation (browning). We evaluated the statistical significance of the residual trend at a 95% significance level to determine whether the residuals indicate a significant anthropogenic impact.

Pearson correlation

Pearson's correlation analysis was applied to examine the pixel-wise relationship between NDVI and key climatic parameters, such as precipitation, mean air temperature, land surface temperature, and potential evapotranspiration. Pearson's correlation coefficient was computed to quantify the strength and direction of these relationships. A p-value below 0.05 was used to determine statistical significance, indicating a meaningful correlation between NDVI and the climatic variables analyzed.

Results

Spatio-temporal distribution in NDVI across South Asia

NDVI serves as a key indicator of vegetation health, ecological conditions, agricultural productivity, and the combined impacts of climatic and anthropogenic activities. Figure 1 presents country-level NDVI trends based on annual mean values for each South Asian country. A notable upward NDVI trend is observed in India, Nepal, Bangladesh, and Pakistan, indicating enhanced vegetation health driven by afforestation efforts, advancements in agricultural practices, and sustainable land management strategies aimed at climate adaptation. The consistent upward trajectory shown by polynomial trend lines demonstrates the success of large-scale conservation programs. The annual anomalies illustrate the inter-annual variations in NDVI. Negative anomalies correspond to some climatic extremes, such as droughts, heatwaves, or extreme weather events, while positive anomalies indicate favorable climatic conditions conducive to vegetation growth. Afghanistan, in particular, exhibits high variability in NDVI due to prolonged drought conditions and political instability, which have severely impacted agricultural productivity. Conversely, India, Pakistan, Bangladesh, and Nepal display substantial positive anomalies, which reflect the investments in ecological restoration. For example, Pakistan's Ten Billion Tree Tsunami project, launched initially in Khyber Pakhtunkhwa in 2014 and expanded nationwide in 2019, has effectively restored millions of hectares of forest land. Similarly, India's Green India Mission aims at extensive afforestation and land restoration. Bangladesh has actively addressed land degradation through initiatives such as the Afforestation and Reforestation Programme under the United Nations Framework Convention on Climate Change (UNFCCC). Nepal has also made considerable progress in vegetation recovery through community-based forest management initiatives started in the 1990s, emphasizing active local participation in reforestation and conservation efforts.

NDVI trend analysis using the Mann–Kendall test and Sen's slope

Spatial patterns of vegetation trends across South Asia (2001–2023) are shown based on the Mann–Kendall (MK) trend analysis and Sen's slope magnitude derived from annual mean NDVI values (Fig. 2a, b). The MK test categorizes vegetation trends into four groups depending on their statistical significance: significant increase, non-significant increase, non-significant decrease, and significant decrease. An additional fifth category represents areas without vegetation cover, which have been masked from the analysis. Areas showing a significant increase in vegetation are predominantly located in western Pakistan, western India, Nepal, and parts of Bangladesh. Regions exhibiting a non-significant increase suggest less consistent vegetation growth, often influenced by interannual variability rather than long-term management practices. Such regions typically include semi-arid areas where vegetation recovery depends more heavily on rainfall events. Conversely, non-significant and significant decreases in NDVI are noted around urban areas such

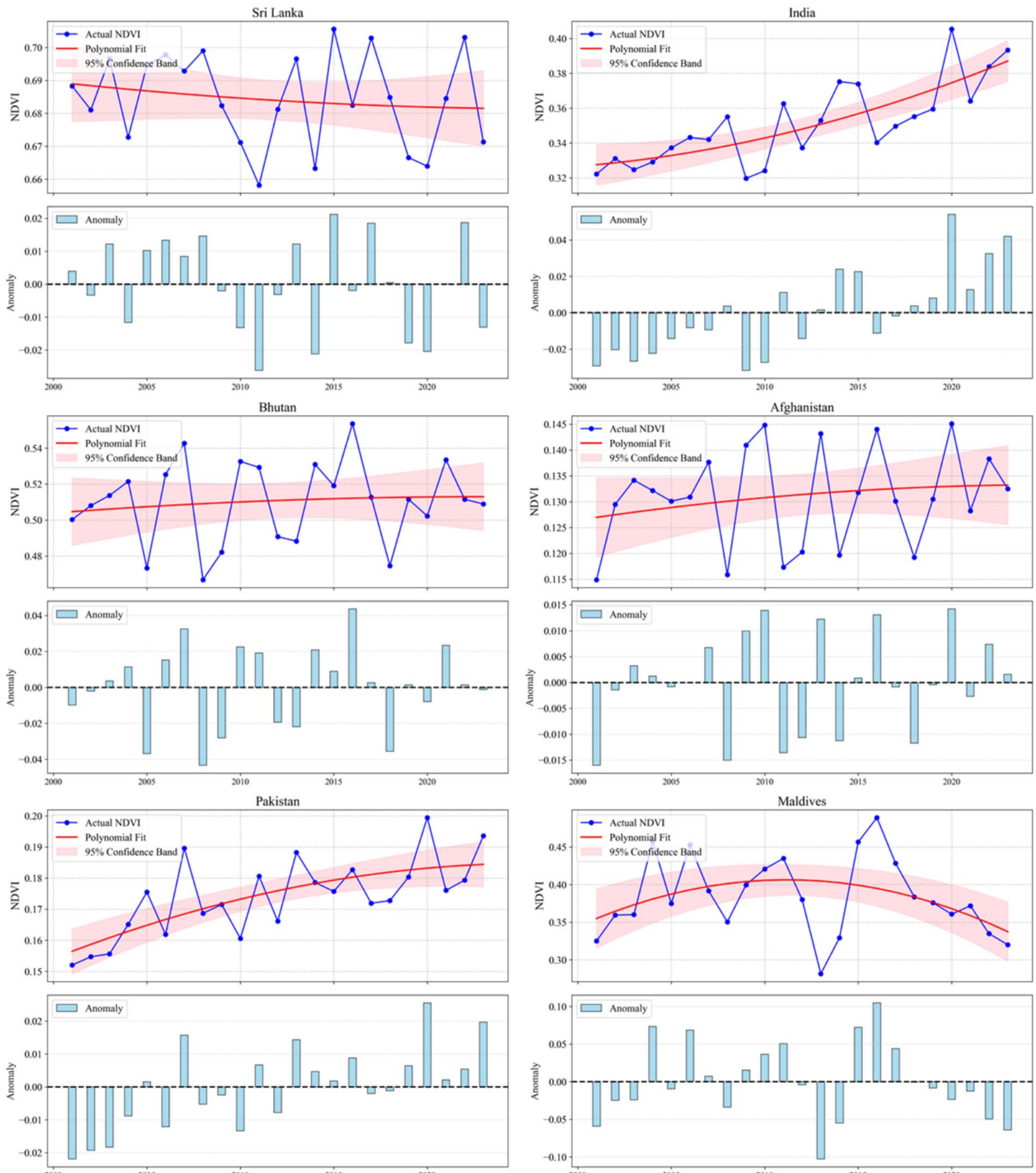

Fig. 1 Temporal trends of mean annual NDVI values and anomalies for South Asian countries (2001–2023), indicating vegetation dynamics and interannual variability

as New Delhi, the states of Haryana and Tamil Nadu in India, the upper and lower Indus basin regions of Pakistan, Northern Sri Lanka, localized areas of the Himalayan foothills, and parts of western Afghanistan. In India and Pakistan, the observed declines are largely associated with urban expansion and increased built-up areas. Declining trends in the Himalayan foothills are linked to deforestation, overgrazing, and reduced precipitation. In Afghanistan, ongoing vegetation decline can be attributed to prolonged drought and climatic

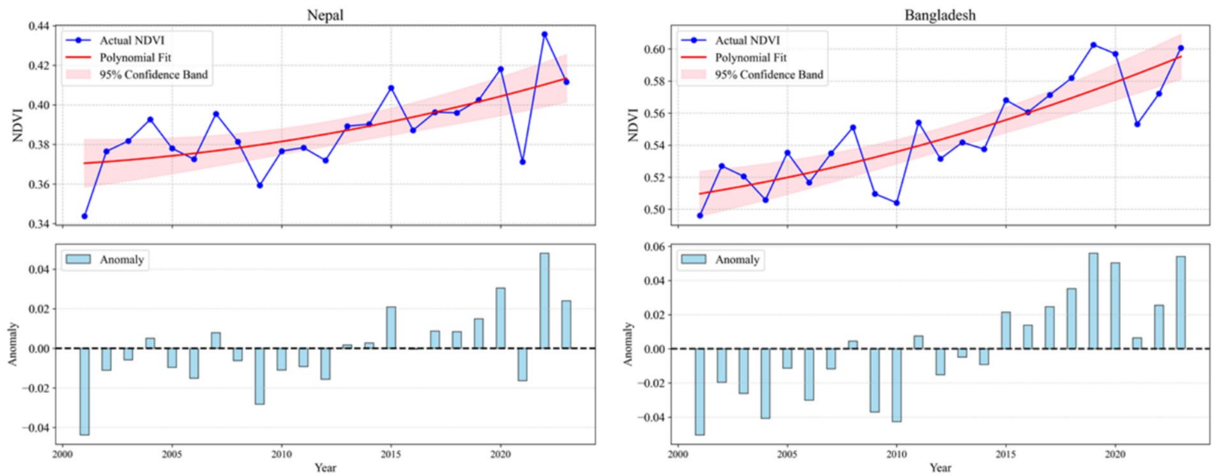

Fig. 1 continued

variability. Sri Lanka's vegetation decline is mainly driven by land degradation and the conversion of forests into other land-use types.

The Sen's Slope magnitude further quantifies the rate of vegetation change. Strong positive slopes, indicating rapid vegetation recovery, are notably observed in specific regions of India and Bangladesh, consistent with the substantially increasing trends identified by the MK test. Regions with low or moderate positive slope values represent areas with gradual vegetation improvements, potentially reflecting slow but steady reforestation or marginal gains in agricultural productivity. Negative Sen's slope values highlight critical areas experiencing vegetation loss, closely corresponding with significant declines identified in the MK analysis.

Climatic factors influencing NDVI across South Asia

The climate significantly shapes natural vegetation patterns and agricultural activities across South Asia. Correlations between precipitation, temperature, and NDVI were analyzed across the region to examine the climatic influence on NDVI. Results indicate that precipitation is the dominant climatic driver affecting vegetation growth, showing a positive correlation with NDVI across approximately 70.5% of the region (Fig. 2c). This strong relationship highlights the importance of rainfall, especially given the region's monsoon-dependent climate. Countries such as India, Bangladesh, Nepal, Bhutan, Pakistan, and Sri Lanka depend heavily on rainfall for both agricultural productivity and natural vegetation health. Regions with statistically significant positive correlations (around 30% of the area) include semi-arid zones like Punjab (across both Pakistan and India), Rajasthan in India, western Afghanistan, and southern India, where vegetation is especially sensitive to variations in moisture availability. These results suggest that even minor disruptions in rainfall patterns, such as delayed monsoons or decreased rainfall, can substantially impact vegetation distribution and health.

Temperature demonstrates a more varied influence on NDVI, with a positive correlation observed across only 18.8% of the region, and statistically significant positive correlations limited to just 2.1% (Fig. 2d). The positive correlations are primarily concentrated in temperate and high-altitude regions, including Nepal, Bhutan, and northern Pakistan, where warmer temperatures extend growing seasons, thus enhancing vegetation growth. In contrast, arid and semi-arid regions, such as Afghanistan, Pakistan, and certain parts of India, typically exhibit negative correlations between temperature and NDVI, reflecting the harmful impacts of rising temperatures. Increased temperature in these areas intensifies evapotranspiration, leading to soil moisture deficits and, consequently, a reduction in vegetation cover.

Overall, precipitation showed a stronger influence than temperature on vegetation dynamics in South Asia, particularly in regions dependent on rainfall for vegetation growth. Temperature demonstrated a more localized influence: it supports vegetation growth where moisture is sufficient, yet poses significant challenges in arid and semi-arid zones. Countries such as India and Pakistan, where agriculture heavily relies on rainfall, remain particularly vulnerable to climatic variability. In mountainous countries like Nepal and Bhutan, as well as in the northern parts of India and Pakistan, rising temperatures may initially promote vegetation growth, yet changes in precipitation patterns could still pose risks.

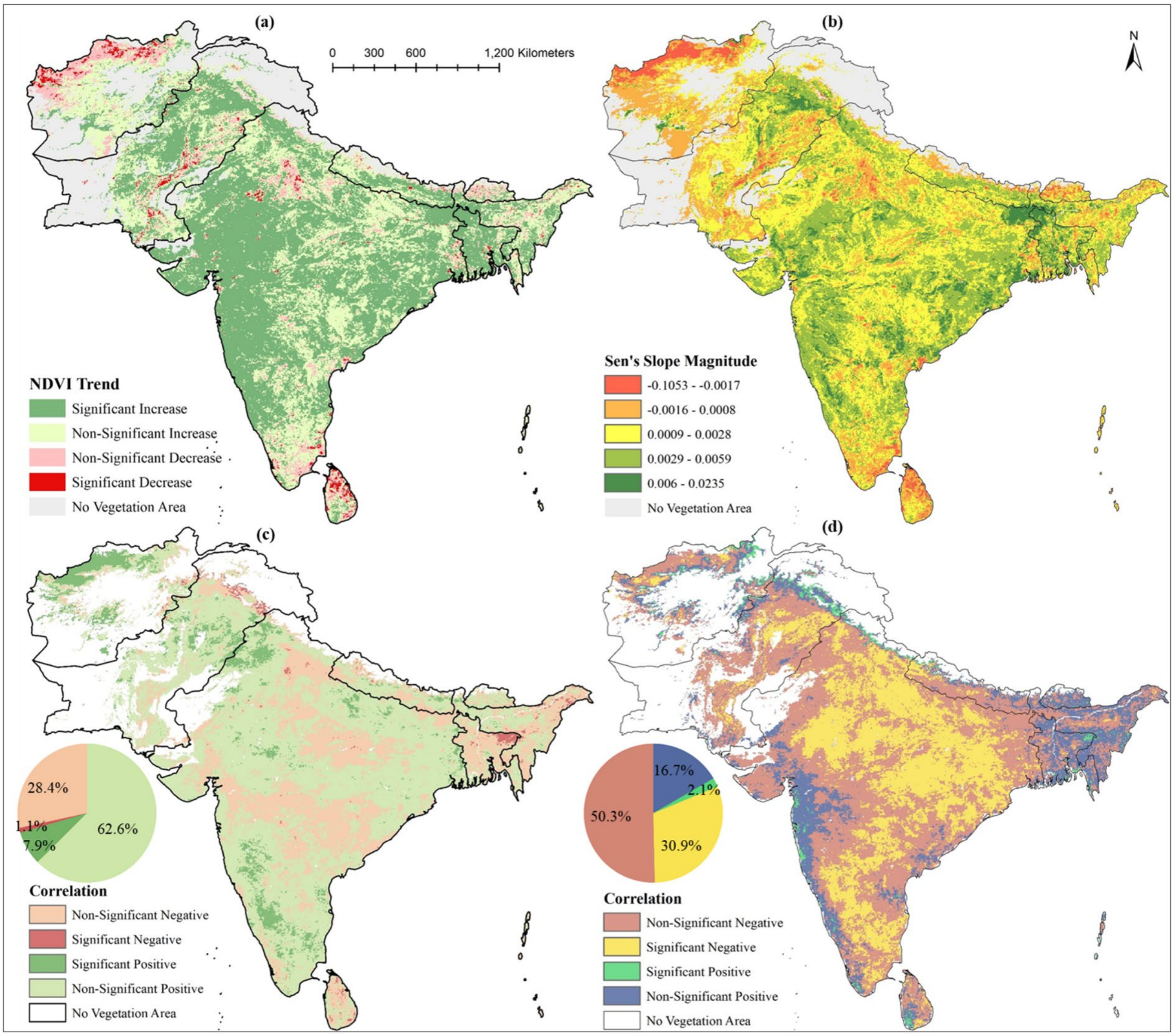

Fig. 2 Spatial distribution of vegetation trends across South Asia (2001–2023): **a** Mann–Kendall trend analysis classified NDVI trends into four distinct categories based on the Z-statistic derived from the test. A significant increase was identified where the Z-value exceeded 1.96, indicating a statistically significant upward trend at the 95% confidence level. A non-significant increase was assigned when the Z-value was positive but did not exceed 1.96, suggesting an upward trend that was not statistically significant. Conversely, a significant decrease corresponded to Z-values below −1.96, indicating a statistically significant decrease. A non-significant decrease was defined by negative Z-values below 0–1.96, indicating a downward trend without statistical significance. **b** Magnitude of vegetation change based on Sen's slope estimator. The map shows areas of vegetation increase and decline, where positive slope values indicate increasing NDVI trends and negative values indicate declining trends. Sen's slope values represent the magnitude of change per year. **c**, **d** The dominant climatic influences on vegetation dynamics are depicted through spatial correlations between NDVI and climatic variables: **c** NDVI and precipitation, and **d** NDVI and temperature. Each map is classified into four categories based on the direction and statistical significance of the Pearson correlation: significant positive, non-significant positive, significant negative, and non-significant negative

Anthropogenic factors affecting vegetation

The residual trend analysis shows the influence of anthropogenic activities on vegetation dynamics in South Asia, beyond the climatic factors of precipitation and temperature alone. Approximately 83.1% of the vegetation areas exhibited positive residual trends, highlighting a predominantly beneficial effect of human interventions (Fig. 3a). Positive trends indicate successful human-led initiatives such as afforestation, expansion and improvement of irrigation systems, sustainable land management, and the conversion of land to productive agriculture, forest, and orchards. These efforts have resulted in vegetation growth exceeding what could be expected based solely on climatic conditions.

However, about 16.9% of vegetated areas showed negative residual trends, highlighting regions where human

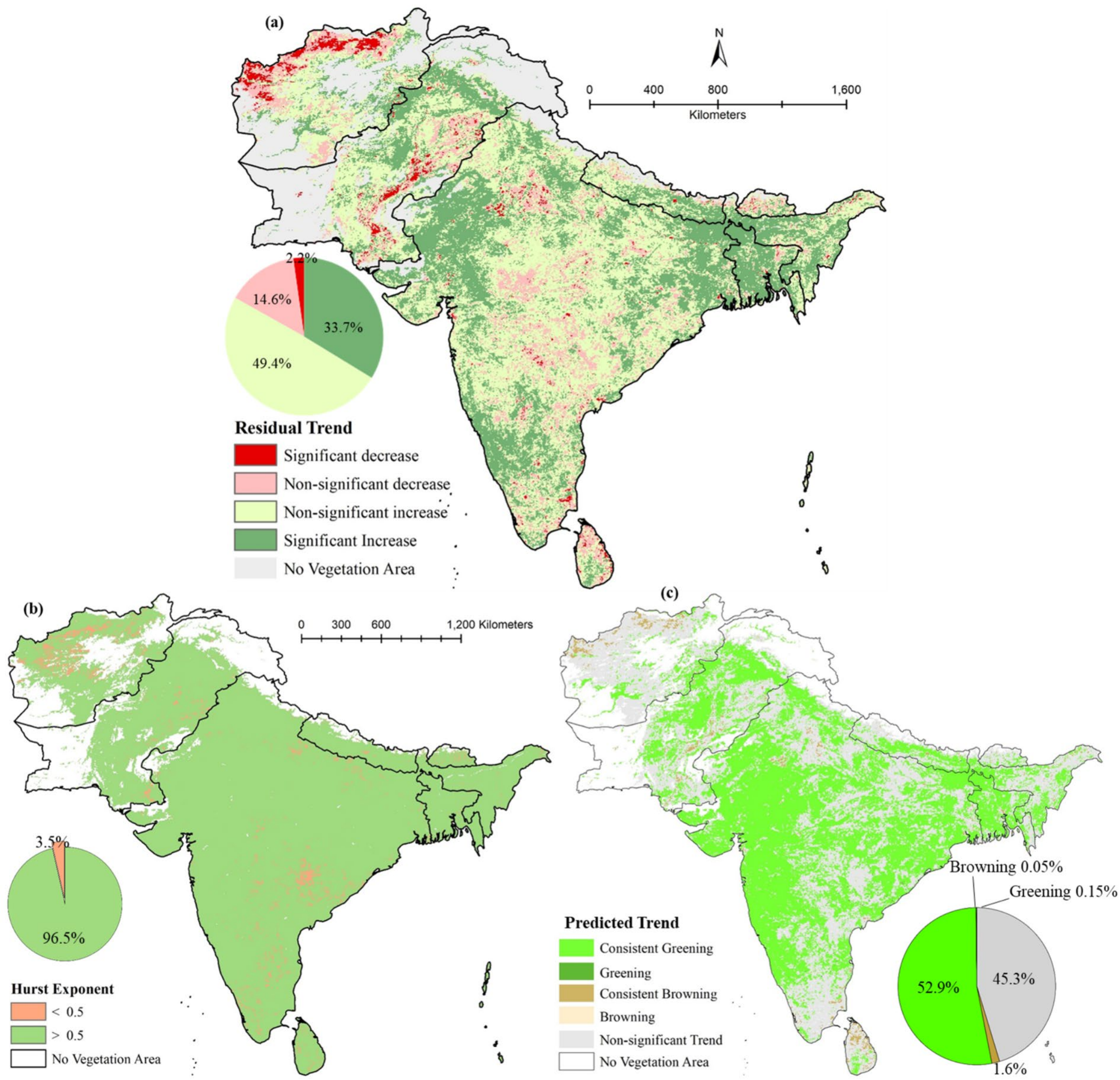

Fig. 3 **a** Spatial analysis of long-term vegetation dynamics using residual and Hurst-based approaches: **a** Residual trend classification based on NDVI, where trends are grouped into significant increase, non-significant increase, non-significant decrease, and significant decrease based on *p*-values; these represent human-influenced vegetation changes after removing climatic effects. **b** Hurst exponent results indicating the persistence of vegetation trends, classified into two categories: Hurst exponent > 0.5 (persistent) and <0.5 (anti-persistent). **c** Predicted vegetation trends derived from the combination of MK and Hurst results, categorized into consistent greening, greening, consistent browning, browning, and non-significant trends

actions such as urbanization, industrialization, deforestation, overgrazing, and excessive groundwater extraction have degraded vegetation cover. For example, negative residuals observed in the Indus basin, particularly around urban centers, reflect the impact of rapid urban expansion and unplanned housing developments. Similarly, a prominent area of negative residuals around New Delhi, India, signifies vegetation loss due to intensive urbanization (Fig. 3a). In the Sundarbans region of Bangladesh, encroachment for settlements and associated land-use changes have negatively influenced vegetation, despite otherwise favorable climatic conditions. In Afghanistan, extensive areas of vegetation decline have occurred due to prolonged droughts, overgrazing, and prolonged political instability, including war and conflict.

Hurst exponent-based analysis of vegetation trends prediction in South Asia

Vegetation dynamics in South Asia are predicted by combining the Hurst exponent with the MK trend results. The Hurst exponent values are classified into two categories: areas with values less than 0.5 (<0.5), indicating anti-persistent vegetation trends likely vulnerable to degradation (browning), and areas with values greater than 0.5 (>0.5), indicating persistent trends likely to maintain their current trajectory (greening). Only 3.5% of the vegetated area falls into the anti-persistent category, highlighting regions highly susceptible to external stressors. Areas without vegetation cover, such as water bodies, barren lands, and snow-covered regions, are excluded from this analysis. Conversely, the persistent category dominates, covering approximately 96.5% of vegetated regions, where these areas are characterized by predictable trends that ongoing greening trends are expected to continue (Fig. 3b and Table 1).

The predicted vegetation trend map categorizes South Asia according to consistent greening and browning trends. Consistent greening is the most extensive category, covering about 52.9% of vegetated areas (Fig. 3c). These regions reflect ongoing vegetation driven by successful reforestation projects, agricultural development, and favorable climatic conditions. A small fraction of the vegetation area (0.15%) exhibits greening trends without strong persistence, whereas consistently declining vegetation (browning) covered about 1.6% of the area, indicating long-term degradation. An even smaller area (0.08%) shows browning trends without persistence. Approximately 45.3% of the vegetated region shows no significant vegetation trend. Overall, the dominance of persistent greening trends across South Asia suggests an encouraging trajectory for vegetation health in the region.

Table 1 Summary of vegetation dynamics by trend classification

Indicator	Category	Area (%) of vegetated region
MK trend analysis	Significant increase	48.5%
	Non-significant increase	40.5%
	Significant decrease	1.5%
	Non-significant decrease	9.5%
Residual trend analysis	Positive residuals	83.1%
	Negative residuals	16.9%
Hurst exponent analysis	Persistent (H > 0.5)	96.5%
	Anti-persistent (H < 0.5)	3.5%

Discussion

The analysis of NDVI trends across South Asia highlights significant spatial and temporal variations driven by both climatic and anthropogenic factors. The Mann–Kendall test results showed a substantial vegetation increase in several areas across South Asia, whereas noticeable declines occurred primarily around urbanized regions and arid zones. These findings align with previous studies, such as Sarmah et al. (2018), who identified predominant vegetation greening in semi-arid and cropland areas such as the Indo Gangetic plains, the Deccan plateau, and parts of Bangladesh. Similar observations emerged from our analysis as well.

Indeed, the increase in vegetation cover observed in our study is largely linked to the expansion and improvement of irrigation facilities, particularly in the semi-arid regions of India and Pakistan. Wang et al. (2017) and Sarmah et al. (2018) also emphasized that irrigation is a primary factor driving vegetation growth across South Asia. According to FAOSTAT (2024), the total harvested area in the region expanded from 12.1 million hectares in 2001 to 14.6 million hectares in 2023, reflecting an increase of approximately 20.7%. Our results support this trend, especially highlighting gradual increases in cultivated land in India, Bangladesh, and Sri Lanka. However, Bhutan presents a contrasting scenario with a sharp decline in agricultural areas (Fig. 4a). In Bhutan, the limited availability of cultivable land, combined with climate change, frequent extreme events, and soil degradation, has negatively impacted agricultural productivity. This combination has increased the vulnerability of Bhutan's farming systems, exacerbating both the land loss and declining productivity (Chhogyel and Kumar 2018).

Precipitation is another key driver influencing vegetation dynamics in South Asia, where monsoons significantly determine vegetation health and distribution. Annual variations in precipitation directly influence NDVI values, reflecting changes in vegetation density and coverage. For instance, years of low precipitation, such as 2002, 2008, 2009, 2012, 2018, and 2019 (as shown in Fig. 4b), clearly correspond to negative NDVI anomalies depicted in Figure S1, emphasizing precipitation's direct impact on regional vegetation. Sarmah et al. (2018) similarly observed the high sensitivity of South Asian vegetation to precipitation variations, which is consistent with our findings, indicating that over 70% of vegetated areas exhibit a positive correlation with precipitation (Fig. 2c). Ali et al. (2019) also reported increased vegetation linked to higher precipitation, particularly in rainfed regions. Increasing rainfall contributes positively to vegetation health and density (Ali et al. 2020b) and promotes vegetation growth, especially in dry zones (Sarmah et al. 2018).

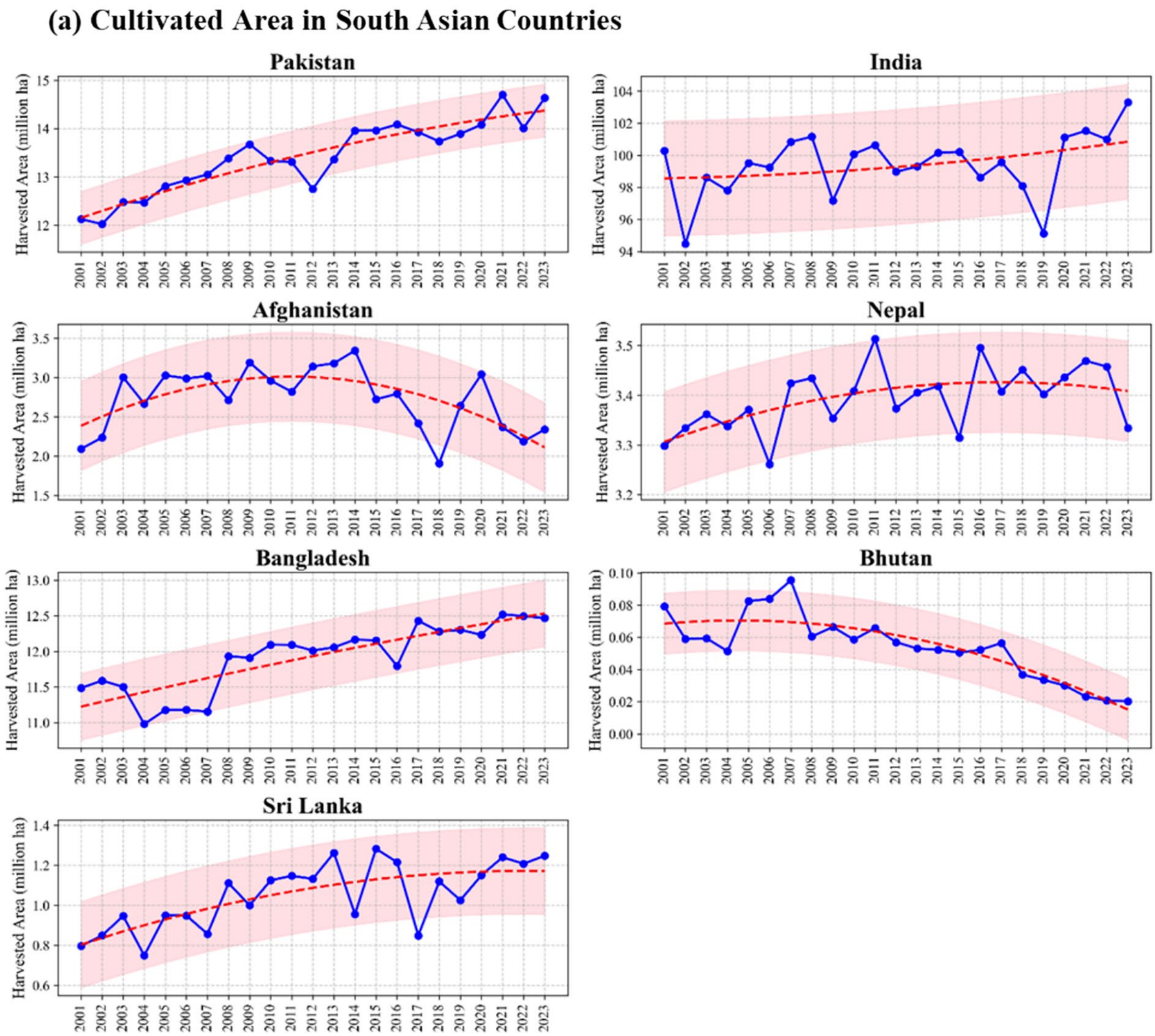

Fig. 4 **a** Spatiotemporal trends of cultivated areas in South Asian countries (2001–2023), highlighting changes in agricultural land use. **b** Spatiotemporal trends of annual precipitation across South Asian countries (2001–2023), illustrating climatic variability and its implications for vegetation dynamics

While a widespread greening trend was observed across South Asia, similar patterns have been documented globally in China, Europe, and North America, largely due to extensive afforestation initiatives and agricultural intensification (Prăvălie et al. 2022; Liu 2023). Nonetheless, this greening is not uniformly distributed, as prolonged droughts and ongoing land degradation have led to vegetation browning in several arid and semi-arid regions (Qu et al. 2020). Therefore, broader global vegetation studies are essential for a deeper understanding of vegetation dynamics.

Although the MODIS NDVI dataset offers advantages in terms of temporal continuity and regional coverage, it still has some limitations. In densely forested regions such as the Himalayan foothills, NDVI values tend to saturate. Additionally, in these mountainous areas, the 1 km resolution may introduce mixed-pixel effects, limiting sensitivity to finer-scale vegetation dynamics. These could lead to an underestimation of subtle forest degradation or afforestation processes. Therefore, future studies are encouraged to complement MODIS-based analyses with higher-resolution datasets like Sentinel-2 or Landsat, which can more accurately capture vegetation dynamics and enhance the detection of localized trends in ecologically complex regions. Another key limitation of this study is the absence of field-based validation for NDVI trends, residual model results, and Hurst exponent predictions. Due to the vast spatial extent and

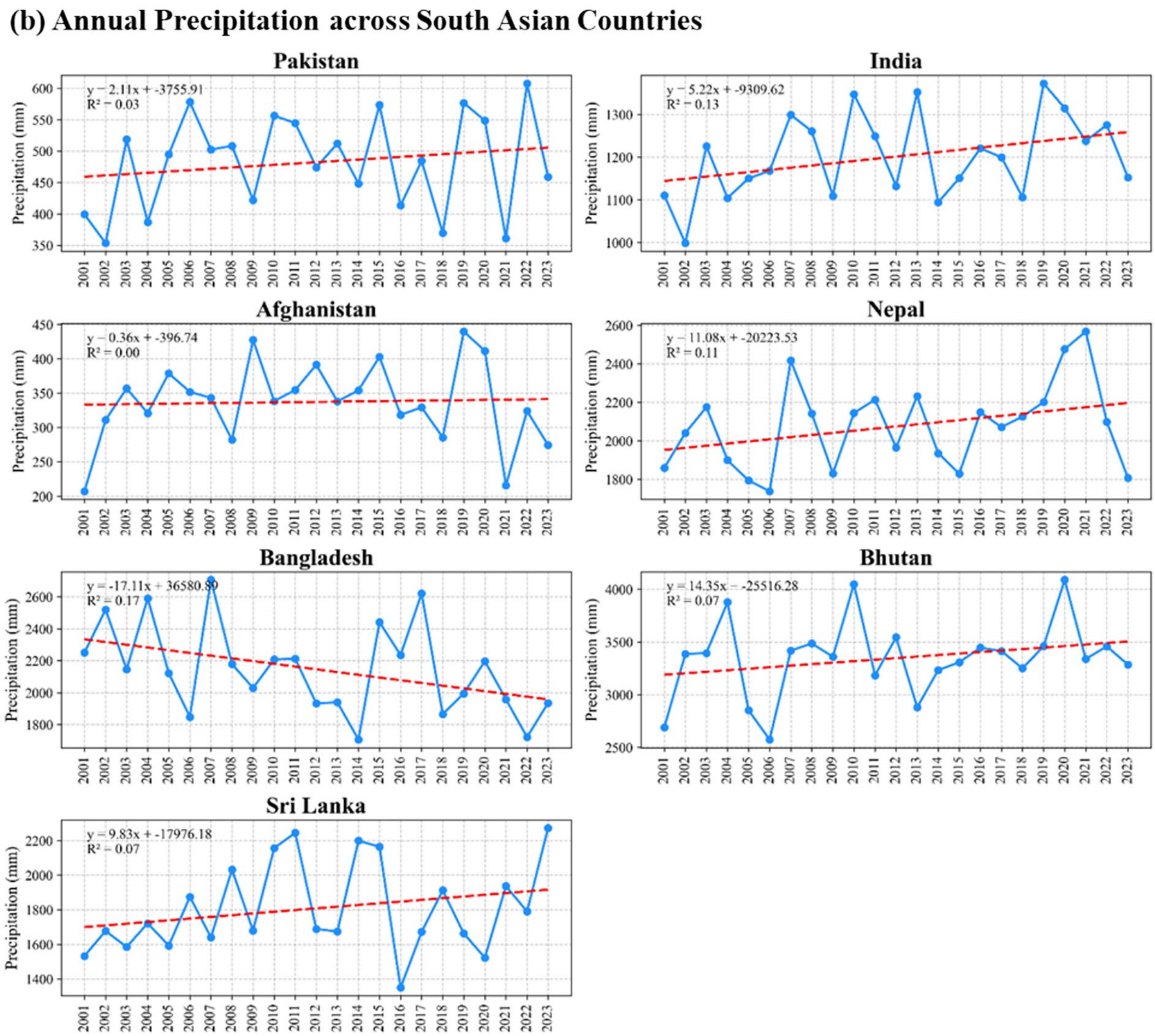

Fig. 4 continued

ecological diversity of South Asia, field-based validation is difficult to achieve. Future studies should incorporate alternative validation strategies such as comparison with FAO land cover statistics, national forest inventories, or higher-resolution datasets, e.g., Landsat, Sentinel-2, or VIIRS, to verify observed vegetation trends and model results. It is important to note that the NDVI variations to climate drivers in this study is based on Pearson correlation analysis, which does not imply causality or establish the direction of influence. Therefore, the observed correlations are interpreted as indicative relationships rather than definitive causal links. Additionally, lagged effects and feedback mechanisms between vegetation and climate were not explored in this study. In addition, while the Hurst exponent is a valuable statistical tool for assessing the persistence of vegetation trends, it assumes stationarity in the time series and is sensitive to the dataset's temporal length. The values greater than 0.5 suggest that greening may continue, but they should not be interpreted as indicators of ecological resilience. Vegetation patterns remain vulnerable to sudden changes driven by land-use changes, government policy shifts, or extreme climatic events.

Conclusions

This study provides a detailed assessment of vegetation dynamics in South Asia, highlighting the roles of both climate and human activities in shaping vegetation trends. The analysis revealed a widespread greening trend across the region, primarily driven by afforestation programs, improved irrigation practices, and sustainable land management efforts. However, vegetation decline was clearly observed in areas undergoing rapid urbanization, where deforestation and land-use changes have led to notable vegetation losses.

Precipitation emerged as the most influential climatic factor influencing vegetation health, with more than 70% of the study region showing a positive correlation between precipitation and NDVI. The impacts of temperature were more variable; increased temperatures supported vegetation growth in high-altitude regions while negatively affecting vegetation health in arid and semi-arid zones. Residual trend analysis further emphasized the importance of human interventions: approximately 83.1% of vegetated areas showed positive trends linked to proactive human activities, while 16.9% exhibited negative residuals associated with urbanization and land degradation.

The Hurst exponent analysis indicates that current greening trends in most parts of the region are likely to continue, reflecting persistence vegetation improvements. Nevertheless, certain areas remain vulnerable to persistent vegetation decline, requiring targeted conservation efforts. Given increasing pressures from population growth, urbanization and climate change, proactive and strategic land management practices are essential for maintaining healthy vegetation. Recommended policy measures include large-scale afforestation, climate-resilient agricultural practices, and urban green-space planning to minimize vegetation loss and enhance ecological resilience across South Asia.

Supplementary Information

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Additional file 1.

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Author contributions

G.R. led the original draft writing, performed the visualizations, developed the software, designed the methodology, conducted the investigation and formal analysis, curated the data, and contributed to conceptualization. U.F. and M.-K.J. contributed to the investigation, conceptualization, data curation, and visualization. H.-H.K. supervised the project and contributed to writing, review & editing, visualization, validation, software, resources, methodology, investigation, funding acquisition, formal analysis, and conceptualization. All authors reviewed and approved the final manuscript.

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Data availability

The MODIS NDVI (MOD13A2) data, LST (MOD11A2) data, and the ERA5 reanalysis data (temperature and precipitation) are available from https://github.com/GhaniRahman-UoG/ERA5-Dataset-download-.

Declarations

Competing interests

The authors declare no competing interests.

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