

Comparative Analysis of Summer Urban Vegetation Moisture and Greenness in the Bangkok Metropolitan Region Using Sentinel-2 Data

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Abstract—Rapid urbanization in tropical megacities intensifies environmental stress on urban vegetation, particularly during the summer season characterized by high temperatures, elevated evapotranspiration, and limited moisture availability. This study examines spatiotemporal patterns of summer urban vegetation greenness and moisture in the Bangkok Metropolitan Region (BMR), Thailand, using Sentinel-2 multispectral imagery. Vegetation conditions were evaluated for the summers of 2016, 2018, 2022, and 2024 using the Normalized Difference Vegetation Index (NDVI), Green Normalized Difference Vegetation Index (GNDVI), and Normalized Difference Moisture Index (NDMI). Pearson correlation analysis was applied to investigate relationships among vegetation greenness, photosynthetic activity, and moisture status under urban environmental stress. The results show that mean summer NDVI and GNDVI values remained relatively stable throughout the study period, indicating that average vegetation greenness has been maintained despite ongoing urban expansion. However, declining maximum NDVI values and increasing spatial heterogeneity reveal a gradual loss of dense and healthy vegetation, particularly in peri-urban areas. NDMI analysis indicates persistently low to slightly positive mean values, reflecting widespread summer water stress across the BMR, with clear contrasts between moisture-rich peripheral zones and the highly urbanized core. Strong positive correlations between NDVI and GNDVI confirm their effectiveness in representing overall vegetation vigor, while moderate correlations between greenness indices and NDMI highlight a partial decoupling between visual greenness and moisture availability. These findings suggest that maintaining average vegetation greenness alone is insufficient to sustain key ecosystem services in rapidly urbanizing tropical cities and emphasize the need to integrate vegetation structure and moisture considerations into urban green infrastructure planning.

Keywords—urban vegetation, Normalized Difference Vegetation Index (NDVI), Green Normalized Difference Vegetation Index (GNDVI), Normalized Difference Moisture Index (NDMI), Bangkok metropolitan region

I. INTRODUCTION

Urban areas represent complex socio-environmental systems where human activities and natural processes are closely intertwined. Rapid urbanization, driven by population growth, economic development, and infrastructure expansion, has fundamentally transformed land-use patterns and environmental conditions in cities worldwide [1, 2]. The Bangkok Metropolitan Region (BMR) is one of the fastest-growing urban agglomerations in Southeast Asia, covering approximately 7762 km² across six provinces and accommodating more than 10.9 million residents as of 2024 [3–5]. This rapid expansion has intensified pressure on

environmental resources, particularly urban green spaces that are essential for maintaining environmental quality and human well-being.

Urban vegetation provides a wide range of ecosystem services that are closely linked to social and environmental sustainability, including microclimate regulation, air quality improvement, and the mitigation of heat-related health risks [6, 7]. In densely built environments such as Bangkok, green spaces also contribute to residents' physical comfort and psychological well-being, making them a critical component of livable and resilient cities. However, continuous urban development and infrastructure expansion in the BMR have the potential to influence the distribution and condition of urban vegetation, which may affect environmental quality and ecosystem functions during periods of extreme climate conditions [8, 9].

In tropical megacities, the summer season represents a period of heightened environmental and social stress due to high temperatures, intense solar radiation, elevated evapotranspiration, and limited soil moisture availability. These conditions directly affect vegetation health and moisture status, while indirectly influencing human thermal comfort and exposure to heat-related risks. Understanding the spatial patterns of vegetation greenness and moisture during summer, therefore, provides important insights into how urban environments respond to climatic stress and how effectively green spaces can support human–environment interactions under extreme conditions. Studies using remote sensing and urban climate data indicate that vegetation cover and its moisture dynamics play a critical role in mitigating urban heat stress by cooling surface temperatures and influencing local microclimates through shade and evapotranspiration processes, which directly affect thermal comfort in cities experiencing intense summer heat. These findings highlight vegetation's capacity to modulate dry and moist heat stress in urban settings, underscoring its importance for urban climate adaptation strategies in tropical and other climate zones [10, 11].

Remote sensing has become a widely used tool in environmental social science for assessing urban environmental conditions at regional scales, offering consistent and spatially explicit information that can inform urban planning and environmental management. Satellite-derived indices such as the Normalized Difference Vegetation Index (NDVI), Green Normalized Difference Vegetation Index (GNDVI), and Normalized Difference Moisture Index (NDMI) are commonly applied to evaluate

vegetation greenness, physiological condition, and moisture stress in urban environments [12, 13]. These indices provide a quantitative basis for examining spatial and temporal variations in vegetation condition and environmental quality. These indices provide a quantitative basis for examining the relationship between urban development and environmental quality.

Accordingly, this study conducts a comparative analysis of summer urban vegetation greenness and moisture conditions in the Bangkok Metropolitan Region using Sentinel-2 imagery for the years 2016, 2018, 2022, and 2024. By analyzing NDVI, GNDVI, and NDMI and examining their statistical relationships, this research aims to reveal spatial patterns of vegetation greenness, physiological condition, and moisture stress during the most climatically stressful period of the year. The findings contribute to environmental social science by highlighting how urban environmental conditions reflect the interaction between human activities and natural systems, and by providing evidence-based information to support sustainable urban planning and environmental governance in rapidly urbanizing tropical cities.

II. STUDY AREA

The Bangkok Metropolitan Region (BMR) covers approximately 7761.60 sq. km. [14] and is located between 13°45' N and 100°31' E in the central region of Thailand. It comprises six provinces: Bangkok, Nonthaburi, Pathum Thani, Samut Prakan, Nakhon Pathom, and Samut Sakhon [3]. As of November 2024, the total population of the BMR was approximately 10,907,911, with an average density of 1405.37 persons per sq. km., according to the Bureau of Registration Administration [5]. The BMR has an annual mean temperature of around 29 °C, with the highest values typically observed in April and the lowest in December. Annual precipitation ranges between 1000 and 1200 mm, peaking in September and reaching the lowest levels in February. The region's potential evapotranspiration exceeds 2229 mm per year, with the highest values occurring between February and May, and the lowest from December to January [15].

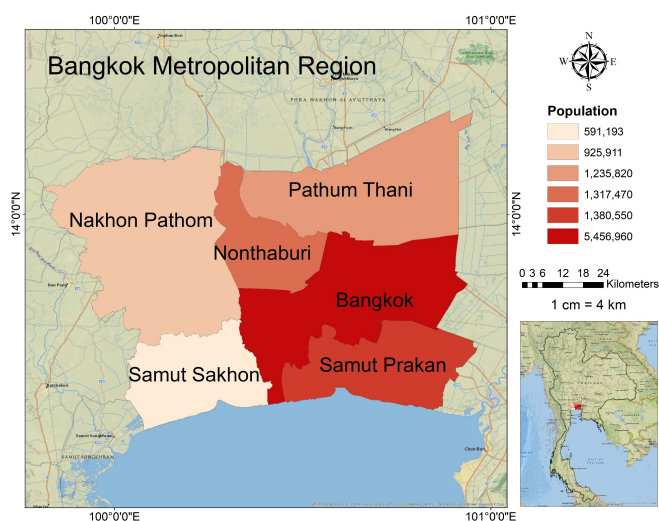


Fig. 1. Bangkok Metropolitan Region (Source: National Geographic, Esri, Garmin, HERE, UNEP-WCMC, USGS, NASA, ESA, METI, NRCAN, GEBCO, NOAA, increment P Corp).

Region (BMR). (1) Summer (mid-February to mid-May): This season begins after the retreat of the northeast monsoon (NE wind) and the arrival of the southwest monsoon (SW wind). During this period, the sun is nearly perpendicular to the ground, resulting in higher temperatures compared to other seasons and consequently higher potential evapotranspiration. Occasionally, the NE wind regains strength and moves southward, colliding with the incoming SW wind, which can lead to thunderstorms and hail. (2) Rainy season (mid-May to mid-October): Influenced by the southwest monsoon, the monsoon trough, and tropical cyclones, this period is characterized by moderate to very high rainfall. (3) Winter (mid-October to mid-February): Beginning with the return of the NE wind and the retreat of the SW wind to lower latitudes, this season brings cooler, drier conditions, with little to no rainfall [15–17]. During winter, many trees shed their leaves to reduce transpiration, leading to a temporary decline or degradation in vegetation cover. Therefore, this study focuses on evaluating seasonal urban vegetation specifically during the summer and winter, as these two seasons represent the most significant contrasts in temperature and humidity. The study area is illustrated in Fig. 1 and Table 1.

Table 1. Principal description of Bangkok Metropolitan Region: BMR [5]

Province/ Region	Total Population (person)	Area (km ²)	Density (person/km ²)	House (Place)
Bangkok	5,456,958	1568.7	3478.6	3,299,048
Nonthaburi	1,317,472	622.3	2117.1	767,802
Pathum Thani	1,235,823	1525.9	809.9	715,206
Nakhon Pathom	925,911	2168.3	427.0	441,998
Samut Prakan	1,380,554	1004.5	1374.4	782,711
Samut Sakhon	591,193	872.3	677.7	323,000
BMR	10,907,911	7762.0	1480.8	6,329,765

III. MATERIALS AND METHODS

This study aimed to assess summer urban vegetation greenness, physiological condition, and moisture status in the Bangkok Metropolitan Region (BMR), Thailand, using Sentinel-2 imagery. The focus on the summer season reflects the period of maximum environmental stress in tropical urban areas, characterized by high temperatures, elevated evapotranspiration, and increased vegetation water demand. Such conditions strongly influence vegetation health and moisture availability across urban landscapes.

Sentinel-2, part of the Copernicus programme, provides multispectral imagery suitable for monitoring vegetation, soil, and built-up surfaces, with a revisit time of approximately 10 days. The sensor includes 13 spectral bands with spatial resolutions of 10, 20, and 30 m and an orbital swath width of 290 km [18]. Sentinel-2 images were obtained from the Copernicus Data Space Ecosystem, and scenes with cloud cover below 20% were selected to minimize atmospheric interference. To capture recent urban dynamics, satellite images from the summers of 2016, 2018, 2022, and 2024 were analyzed. These specific years were selected based on the availability of cloud-free Sentinel-2 imagery during the summer season. In tropical regions such as Bangkok, persistent cloud cover significantly limits the availability of suitable satellite data. Therefore, the selected years represent the most reliable observations for capturing summer

There are three main seasons in the Bangkok Metropolitan

vegetation conditions while minimizing atmospheric interference. Details of the selected images are presented in Table 2.

Three spectral indices were employed to evaluate vegetation greenness, physiological condition, and moisture status: the Normalized Difference Vegetation Index (NDVI), Green Normalized Difference Vegetation Index (GNDVI), and Normalized Difference Moisture Index (NDMI). The formulations of these indices are given in Eqs. (1)–(3), and their interpretations are presented in Table 3.

$$NDVI = \frac{NIR-RED}{NIR+RED} \quad (1)$$

$$GNDVI = \frac{NIR-Green}{NIR+Green} \quad (2)$$

$$NDMI = \frac{NIR-SWIR}{NIR+SWIR} \quad (3)$$

$$r = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2} \sqrt{\sum_{i=1}^n (y_i - \bar{y})^2}} \quad (4)$$

where *Green*, *NIR*, and *SWIR* mean spectral bands, Green, Nir-Infrared, and Short-Wave Infrared bands, respectively. However, *NDVI*, *GNDVI*, and *NDMI* have the values between -1 to 1 , x and y refer to each VI.

Table 2. Description of Sentinel-2 satellite images data

Year	Date	Type	Path/Row
2016	12 April 2016	L2A	T47PPQ
			T47PQR
			T47PNR
			T47PPR
2018	12 April 2018	L2A	T47PPQ
			T47PQR
			T47PNR
			T47PPR
2022	16 April 2022	L2A	T47PPQ
			T47PQR
			T47PNR
			T47PPR
2024	30 April 2024	L2A	T47PPQ
			T47PQR
			T47PNR
			T47PPR

Table 3. Interpretation of NDVI, GNDVI, and NDMI

VI	Value	Description	Color in map
NDVI [19–22]	<0.0	Water or non-vegetated surfaces	Blue
	0.0–0.2	Bare soil, Build up, Rock, Sand, Snow, Cloud	Orange
	0.2–0.3	Shrub and grassland	Yellow
	0.3–0.5	Sparse and unhealthy forest	Light Green
	>0.5	Density and healthy forest	Dark Green
GNDVI [20]	<0.0	Water or non-vegetated surfaces	Blue
	0.0–0.2	Low chlorophyll activity	Light Yellow
	0.2–0.3	Moderate photosynthetic activity	Yellow
	0.3–0.5	High photosynthetic activity	Light Green
	>0.5	Very high photosynthetic activity	Dark Green
NDMI [21, 22]	<0.0	Extremely dry / Built-up / Surface water	Blue
	0.0–0.2	Low canopy cover, high water stress	Light Green
	0.2–0.4	Mid canopy cover, low water stress	Yellow
	>0.4	Very high canopy cover, no water stress	Dark Green

Note: Interpretation follows commonly adopted thresholds in urban and regional remote sensing studies [19–22].

All satellite image processing and analysis were conducted using Geographic Information System (GIS) and remote sensing software. The downloaded Sentinel-2 Level-2A

images were first preprocessed by applying cloud masking using the Scene Classification Layer (SCL) to remove cloud and shadow pixels. The images were then clipped to the boundary of the Bangkok Metropolitan Region (BMR) and resampled to a spatial resolution of 10 meters where necessary.

Vegetation indices (NDVI, GNDVI, and NDMI) were calculated on a pixel-by-pixel basis using the corresponding spectral bands (Green, NIR, and SWIR). The resulting index maps were used to analyze spatial patterns of vegetation condition across the study area. Subsequently, zonal statistical analysis was performed to derive descriptive statistics, including minimum, maximum, mean, and standard deviation values for each index and each study year.

To ensure consistent spatial comparison across different years, a point-based sampling approach was applied. A total of 1638 sample points were generated across the Bangkok Metropolitan Region (BMR) using a fishnet grid technique in a GIS environment. The fishnet grid was designed to provide uniform spatial coverage of the study area, allowing each point to represent local vegetation and surface conditions. The sampling density was determined to balance spatial representativeness and computational efficiency.

Each sample point was used to extract corresponding NDVI, GNDVI, and NDMI values from the raster datasets for each study year. This approach enables direct point-to-point comparison of vegetation and moisture conditions across different time periods and reduces bias associated with spatial aggregation.

To examine interactions between vegetation condition, moisture availability, and urban development, Pearson correlation analysis was conducted among NDVI, GNDVI, and NDMI. The Pearson correlation coefficient (r) quantifies the strength and direction of linear relationships between indices, with positive values indicating direct relationships and negative values indicating inverse relationships (Eq. (4)). This approach enables the assessment of ecological trade-offs during the summer season.

IV. RESULT AND DISCUSSION

This study investigated summer vegetation greenness, physiological condition, and moisture status in the Bangkok Metropolitan Region (BMR) from 2016 to 2024 using NDVI, GNDVI, and NDMI derived from Sentinel-2 imagery. By combining spatial analysis with descriptive statistics and correlation analysis, the results reveal not only temporal trends in vegetation condition but also growing spatial variability in vegetation health and moisture availability across the metropolitan region. Such satellite-based assessments are increasingly recognized as effective tools for examining human–environment interactions and urban sustainability challenges in rapidly expanding tropical megacities [23–25].

A. Spatial Patterns of NDVI and Urban Vegetation Conditions

As shown in Table 4, mean summer NDVI values across the Bangkok Metropolitan Region (BMR) remained relatively stable throughout the study period, fluctuating only slightly between 0.224 and 0.239. This pattern suggests that, at the metropolitan scale, overall vegetation greenness has

been maintained despite continued urban expansion. Similar findings have been reported in other Asian megacities, where urban greening policies and managed vegetation partially offset vegetation loss when evaluated using average NDVI values [23, 26]. However, reliance on mean values alone obscures important structural changes within the urban vegetation system.

A notable decline in maximum NDVI values after 2018 indicates a gradual reduction in areas characterized by dense and healthy vegetation. Although the present analysis does not directly evaluate land-use change or urban expansion, the observed decline suggests changes in the spatial distribution and condition of vegetation across parts of the Bangkok Metropolitan Region during the study period. Declines in peak NDVI have been linked to reduced ecosystem service capacity, including urban cooling, carbon sequestration, and mitigation of heat-related health risks [26, 27]. Therefore,

while average greenness appears stable, the loss of high-quality vegetation suggests a weakening of critical ecological functions during summer.

Table 4. Summer NDVI, GNDVI, and NDMI values

VI	Year	Max	Min	Mean	SD
NDVI	2016	0.678	-0.216	0.225	0.179
	2018	0.731	-0.265	0.239	0.198
	2022	0.683	-0.255	0.224	0.190
	2024	0.694	-0.32	0.227	0.195
GNDVI	2016	0.628	-0.303	0.239	0.168
	2018	0.61	-0.384	0.231	0.183
	2022	0.607	-0.444	0.217	0.180
	2024	0.622	-0.541	0.231	0.184
NDMI	2016	0.396	-0.361	-0.016	0.130
	2018	0.404	-0.397	0.026	0.133
	2022	0.42	-0.418	0.025	0.133
	2024	0.489	-0.374	0.013	0.141

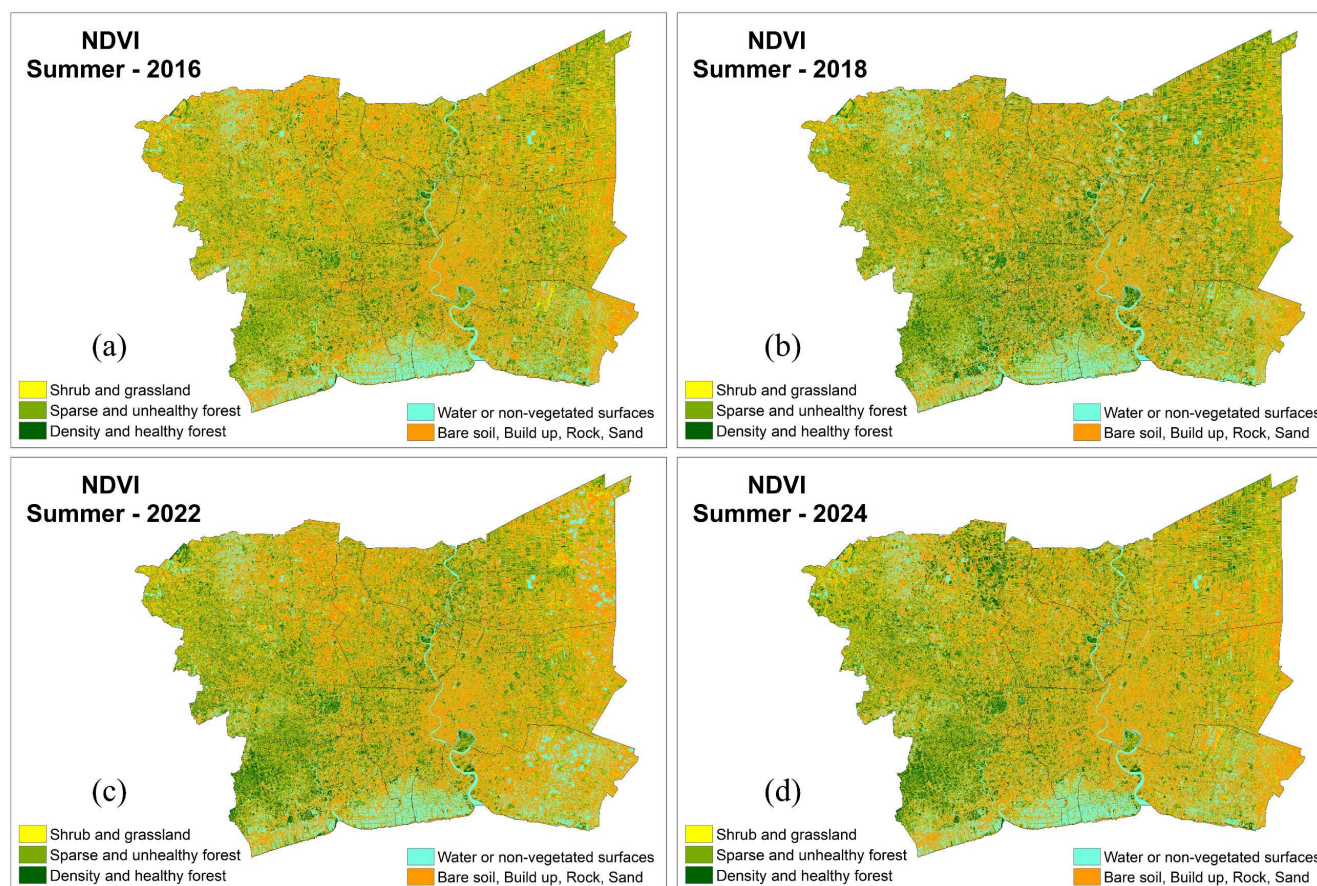


Fig. 2. Summer NDVI of BMR from the Sentinel-2 images (a) 2016, (b) 2018, (c) 2022, and (d) 2024.

The spatial distribution of summer NDVI (Fig. 2) provides further insight into these temporal patterns. Central urban districts, particularly Bangkok and Nonthaburi, consistently exhibited low NDVI values, reflecting extensive impervious surfaces and limited availability of large, contiguous green spaces. In contrast, moderate NDVI values were primarily observed along river corridors, canals, roadside vegetation, and managed urban parks. These areas contribute to localized cooling and ecosystem benefits; however, the distribution of high NDVI patches became increasingly variable over time, suggesting localized differences in vegetation conditions across the study area.

Peripheral provinces initially supported higher NDVI values and contributed disproportionately to regional peak

greenness, particularly in 2018. However, by 2022 and 2024, these areas experienced a noticeable expansion of low NDVI zones associated with changes in surrounding land-cover characteristics and transportation corridors. The loss of peri-urban vegetation is particularly significant, as these areas traditionally function as ecological buffers that regulate microclimate, support biodiversity, and reduce environmental stress in the urban core [26, 28].

Overall, the combined temporal and spatial analysis reveals that while average vegetation greenness in the BMR has remained relatively stable, underlying spatial restructuring and spatial variability in vegetation conditions are increasing. This indicates a change in the spatial distribution of relatively dense vegetation cover toward more

heterogeneity and managed green spaces, with important implications for urban ecological resilience under ongoing urbanization.

B. Vegetation Vigor and Physiological Stress Revealed by GNDVI

Patterns observed in GNDVI (Fig. 3; Table 4) reinforce and extend the NDVI findings by highlighting changes in

vegetation physiological condition. Although mean GNDVI values showed only modest interannual variation, the spatial heterogeneity of vegetation vigor increased markedly over time. GNDVI is especially sensitive to chlorophyll concentration and photosynthetic activity, making it effective for detecting early signs of vegetation stress under high temperature and moisture constraints [29].

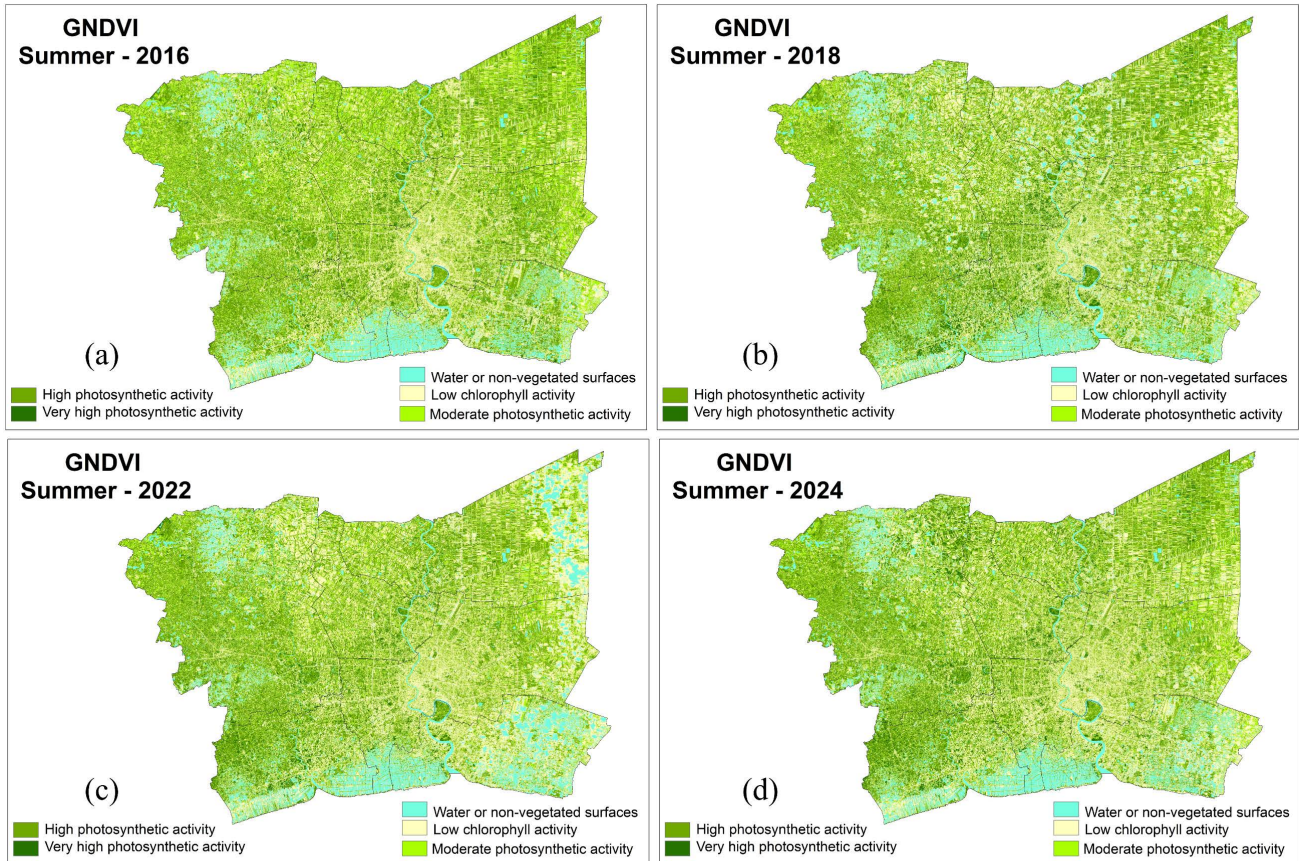


Fig. 3. Summer GNDVI of BMR from the Sentinel-2 images (a) 2016, (b) 2018, (c) 2022, and (d) 2024.

High GNDVI values became increasingly concentrated within well-managed green spaces, such as urban parks, institutional campuses, and irrigated areas. Although these patterns may not be visually prominent at the metropolitan scale in Fig. 3, they are consistently observed when comparing localized areas across different years, particularly in contrast to surrounding built-up zones where GNDVI values remain low. In contrast, densely built-up districts exhibited widespread low GNDVI values, indicating reduced photosynthetic activity and declining vegetation health. This growing spatial disparity suggests that vegetation resilience is becoming increasingly dependent on active management and resource inputs, while unmanaged or residual green areas experience progressive degradation [30, 31].

From a socio-environmental perspective, this uneven distribution of vegetation vigor reflects unequal access to high-quality green spaces and differing capacities for maintenance and irrigation across the metropolitan region. Such inequalities have direct implications for thermal comfort, public health, and environmental justice, particularly during extreme summer conditions [28].

C. Water and Moisture Stress Revealed by NDMI

NDMI analysis (Fig. 4; Table 4) provides critical insight

into vegetation water stress during summer, a period of peak climatic pressure in the BMR. Mean NDMI values remained low to slightly positive across all years, indicating that much of the metropolitan area experiences limited canopy moisture and persistent water stress during the hottest months. NDMI has been widely applied to assess drought sensitivity and vegetation resilience in urban and peri-urban environments under warming climates [30, 32].

Spatially, higher NDMI values were primarily associated with wetlands, irrigated agricultural areas, riverbanks, and selected green spaces with reliable water supply. In contrast, the urban core consistently exhibited low NDMI values, reflecting differences in surface characteristics and water availability across the metropolitan region. By 2024, NDMI patterns exhibited increasing local variability, highlighting sharp contrasts between moisture-rich vegetation patches and extensive areas vulnerable to water stress.

This increasing variability underscores the critical role of water availability in sustaining urban vegetation during summer. Even areas that appear green based on NDVI may experience significant moisture stress, reducing their capacity to provide cooling and other ecosystem services during heat extremes [30].

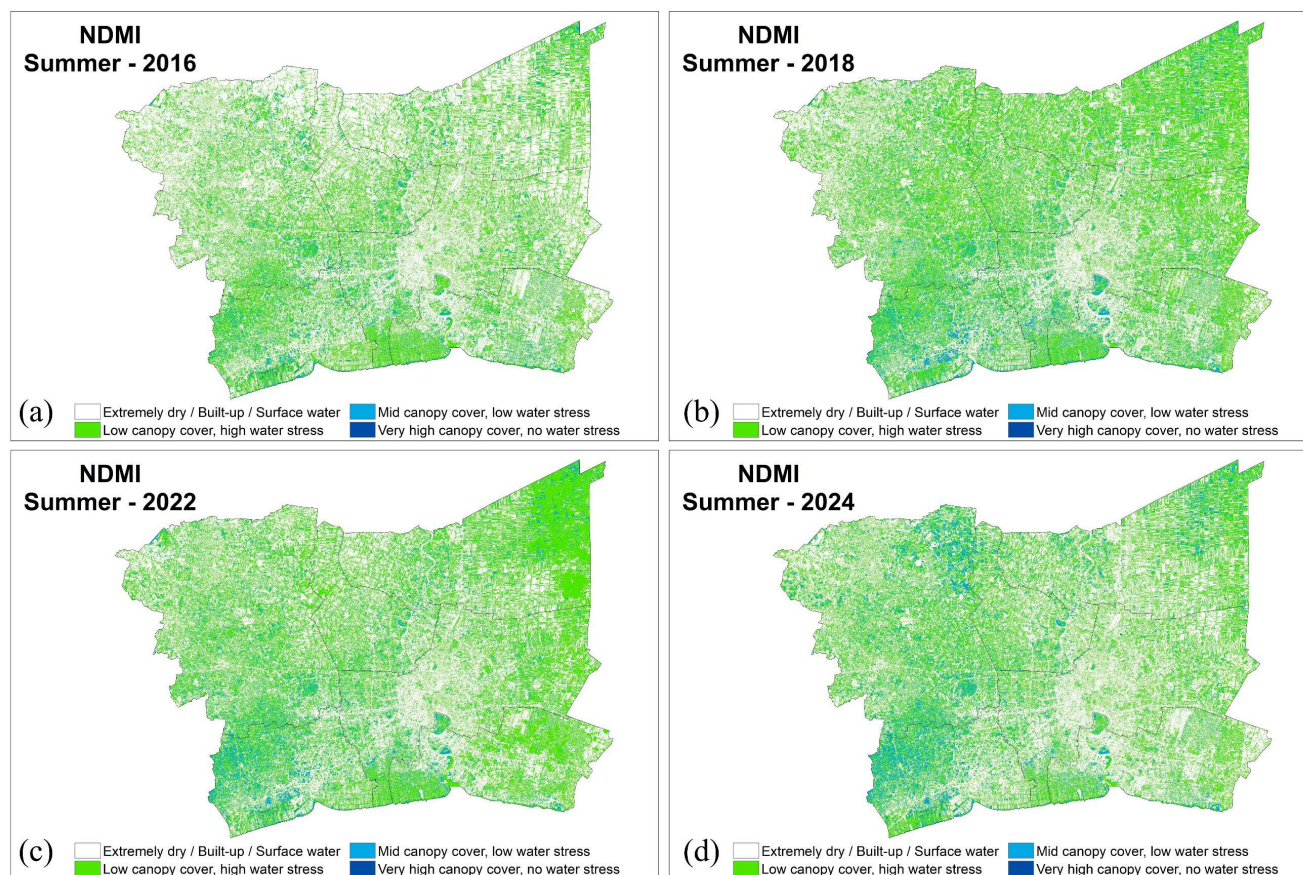


Fig. 4. Summer NDMI of BMR from the Sentinel-2 images (a) 2016, (b) 2018, (c) 2022, and (d) 2024.

D. Relationships among Greenness, Vigor, and Moisture Conditions

Correlation analysis (Table 5) further clarifies interactions among vegetation structure, physiological activity, and moisture status across the BMR. NDVI and GNDVI exhibited consistently strong positive correlations across all study years, confirming that both indices capture closely related aspects of vegetation greenness and photosynthetic activity at the metropolitan scale. Similar findings have been reported in recent urban remote sensing studies, suggesting partial redundancy when both indices are used simultaneously to characterize overall vegetation vigor [24, 29].

Table 5. Correlation between summer NDVI, GNDVI, and NDMI

Year		Correlation coefficient (r)			Coefficient of determination (r^2)		
		NDVI	GNDVI	NDMI	NDVI	GNDVI	NDMI
2016	NDVI	1.000	0.949	0.719	1.000	0.901	0.518
	GNDVI		1.000	0.567		1.000	0.321
	NDMI			1.000			1.000
2018	NDVI	1.000	0.967	0.727	1.000	0.935	0.529
	GNDVI		1.000	0.636		1.000	0.404
	NDMI			1			1.000
2022	NDVI	1.000	0.964	0.686	1.000	0.929	0.470
	GNDVI		1.000	0.575		1.000	0.331
	NDMI			1.000			1.000
2024	NDVI	1.000	0.955	0.737	1.000	0.911	0.543
	GNDVI		1.000	0.634		1.000	0.402
	NDMI			1.000			1.000

In contrast, correlations between NDVI and NDMI were moderate, indicating only partial coupling between vegetation greenness and moisture availability. This decoupling suggests that visually green vegetation does not necessarily indicate adequate water status, particularly in

highly urbanized environments where impervious surfaces disrupt natural hydrological processes and limit soil moisture retention [25, 32]. The weaker correlations between GNDVI and NDMI further imply that chlorophyll-related physiological activity and canopy moisture respond differently to summer heat stress and urban environmental conditions.

E. Urban Vegetation–Moisture Dynamics and Implications for Urban Ecological Resilience

The integration of NDVI, GNDVI, and NDMI provides a more comprehensive understanding of how urban vegetation responds to environmental stress and changing environmental conditions in the Bangkok Metropolitan Region (BMR). The results reveal a clear spatial and functional decoupling between vegetation greenness and moisture availability, indicating that visually green areas do not necessarily correspond to physiologically healthy or well-watered vegetation. This finding is particularly important in tropical megacities, where high evapotranspiration and urban heat intensify vegetation water stress during the summer season.

In addition, interannual variations in vegetation moisture conditions can be partly explained by differences in summer rainfall across the BMR (Fig. 5) derived from Hydro-Informatics Institute of Ministry of Higher Education, Science, Research and Innovation in Thailand [33]. The rainfall data show that 2018 and 2022 experienced relatively higher precipitation across most provinces, particularly in Pathum Thani and Nonthaburi, whereas 2016 and 2024 exhibited comparatively lower rainfall levels. These variations are consistent with the observed NDMI patterns, where higher moisture values in 2018 and 2022 correspond

to wetter conditions, while lower NDMI values in 2016 reflect drier conditions. The observed interannual variability in summer rainfall can be partly attributed to large-scale climate drivers, particularly the El Niño–Southern Oscillation (ENSO) and regional monsoon dynamics. The relatively lower rainfall observed in 2016 and 2024 is likely associated with El Niño conditions, which are known to suppress convection and reduce precipitation over Southeast Asia. In particular, the strong El Niño event during 2015–2016 led to widespread drought conditions across the region, with lingering effects into early 2016. Similarly, the emerging El Niño conditions during 2023–2024 contributed to below-average rainfall in Thailand, weakening the southwest monsoon and limiting moisture transport into the Bangkok Metropolitan Region. These conditions resulted in reduced soil moisture availability and lower NDMI values. In contrast, the relatively higher rainfall observed in 2018 and 2022 may be linked to neutral to weak La Niña conditions and stronger monsoon activity. La Niña phases are generally associated with enhanced precipitation in Southeast Asia due to intensified moisture advection and convective activity [34]. This explains the higher NDMI values observed during these years, particularly in peri-urban and agricultural areas. These findings highlight the combined influence of regional climate variability and local urban conditions in shaping vegetation moisture dynamics in tropical megacities.

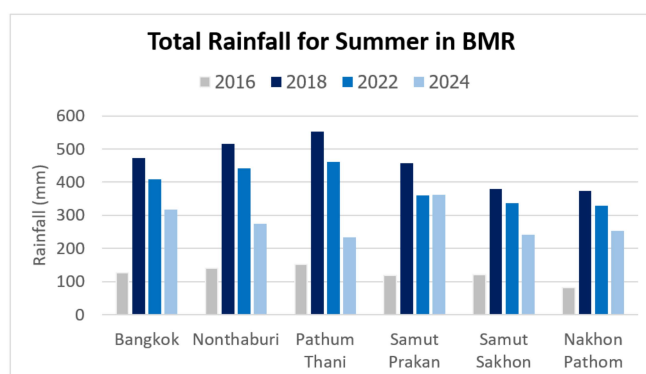


Fig. 5. Summer rainfall of BMR in mm unit.

Seasonal precipitation plays an important role in regulating vegetation moisture dynamics in tropical urban environments, where evapotranspiration demand is high. However, despite increased rainfall in certain years, the persistence of low NDMI values in highly urbanized areas suggests that urban surface characteristics, such as impervious cover and reduced infiltration capacity, limit the effectiveness of rainfall in sustaining vegetation moisture. This indicates that urbanization not only alters vegetation structure but also disrupts the natural water balance, leading to increased vegetation stress even under relatively favorable climatic conditions [35].

The relationships among vegetation indices further highlight a partial decoupling between vegetation greenness and moisture availability. Moderate correlations between NDVI, GNDVI, and NDMI indicate that vegetation can maintain a visually green canopy while experiencing underlying physiological stress due to limited water availability. This finding emphasizes that greenness-based indices alone are insufficient to capture moisture-related stress conditions, and moisture-sensitive indices such as

NDMI are essential for detecting hidden vegetation stress [36].

The spatial heterogeneity observed in NDMI reinforces the importance of water availability as a key limiting factor for urban vegetation resilience. Moisture-rich areas are largely confined to river corridors, irrigated green spaces, and peri-urban zones, whereas highly urbanized districts experience persistent water stress. This pattern is consistent with findings from recent studies demonstrating that land cover type and urban structure strongly influence water balance and vegetation performance [37].

From an urban ecological perspective, these findings reflect a shift toward a greater reliance on managed vegetation and irrigated green spaces and management-dependent green spaces. Urban vegetation is increasingly reliant on artificial irrigation and localized maintenance rather than natural hydrological processes. This shift has important implications for long-term urban resilience, as water-stressed vegetation may have reduced capacity to provide key ecosystem services such as urban cooling, carbon sequestration, and heat stress mitigation. Importantly, these changes may also exacerbate urban health disparities, as reduced cooling capacity and uneven distribution of green spaces disproportionately affect vulnerable populations, increasing exposure to heat stress and related health risks. Enhancing equitable access to functional urban green spaces is therefore essential not only for environmental sustainability but also for reducing health inequalities in rapidly urbanizing environments [38]. Importantly, while spatial patterns suggest potential disparities in vegetation quality and environmental conditions across the BMR, these interpretations should be considered indicative rather than conclusive. Further research incorporating socio-economic and demographic data is required to explicitly assess environmental equity and differential exposure to urban climate risks.

Overall, this study demonstrates that a multi-index remote sensing approach, integrating vegetation structure (NDVI), physiological condition (GNDVI), and moisture status (NDMI), provides a robust framework for understanding the complex interactions between urban development and ecological processes. Such integrated analysis is essential for supporting climate-adaptive urban planning and improving the resilience of tropical megacities under increasing environmental stress.

F. Local-Scale Spatial Variation of Vegetation Greenness, Vigor, and Moisture Conditions

To further illustrate spatial variability that may not be fully discernible at the metropolitan scale, an additional local-scale analysis was conducted using a representative area located in the northern–northeastern part of the Bangkok Metropolitan Region (Fig. 6). This area encompasses a heterogeneous landscape composed of agricultural fields, peri-urban development, transportation infrastructure, water bodies, and built-up surfaces occurring in close spatial proximity. Such a landscape configuration provides a suitable setting for examining fine-scale variations in vegetation condition because transitions between natural, agricultural, and urban environments often generate strong spatial gradients in vegetation structure, physiological activity, and moisture

availability [39].

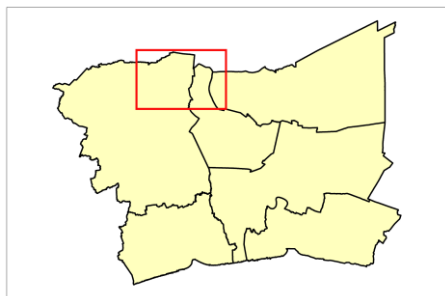


Fig. 6. Location of the selected zooming area within the Bangkok Metropolitan Region (BMR). The area was selected to illustrate local-scale spatial variability across mixed land-cover types.

The NDVI maps (Fig. 7(a)–(d)) reveal substantial local-scale heterogeneity in vegetation greenness across the study period. Although metropolitan-scale NDVI statistics indicated relatively stable average greenness conditions, the zoomed area demonstrates that vegetation responses were not spatially uniform. Areas characterized by agricultural land and managed green spaces exhibited marked fluctuations in NDVI values among years, while urbanized surfaces consistently maintained lower values. Higher NDVI concentrations observed in 2018 and 2024 suggest localized improvements in vegetation density and canopy development, whereas more dispersed distributions of moderate NDVI values in 2016 and 2022 indicate greater spatial variability in vegetation cover. These findings highlight the importance of examining local-scale patterns, as regional averages may conceal substantial spatial differences in vegetation conditions.

The GNDVI results (Fig. 7(e)–(h)) provide additional insights into vegetation physiological performance and photosynthetic activity. Compared with NDVI, GNDVI is more sensitive to variations in chlorophyll concentration and canopy vigor, allowing subtle differences in vegetation condition to be more clearly detected [40]. The spatial distribution of GNDVI indicates that areas exhibiting relatively high vegetation greenness did not always display equivalent levels of physiological activity. In particular, agricultural and managed vegetation areas showed pronounced interannual variability in GNDVI, suggesting that local vegetation performance was influenced by factors such as vegetation type, management practices, and seasonal environmental conditions. This pattern reflects the complex spatial variability in vegetation functioning within mixed urban–agricultural landscapes.

More pronounced temporal variability was observed in the NDMI patterns (Fig. 7(i)–(l)). NDMI is primarily associated with vegetation water content and canopy moisture status and therefore represents a different biophysical characteristic from vegetation greenness [41]. The local-scale comparison demonstrates that vegetation moisture conditions varied considerably among years, with broader distributions of higher NDMI values observed in 2024 relative to earlier years. Importantly, areas exhibiting relatively high NDVI or GNDVI values were not always associated with correspondingly high NDMI values. This finding suggests that vegetation greenness, chlorophyll activity, and moisture status may respond differently to environmental conditions

and therefore exhibit distinct spatial and temporal patterns. Consequently, the use of multiple vegetation indices provides a more comprehensive assessment of vegetation conditions than reliance on a single index alone.

Overall, the local-scale analysis demonstrates that summer vegetation conditions within the Bangkok Metropolitan Region are characterized by substantial local-scale spatial variability across relatively short distances. The coexistence of agricultural land, peri-urban development, water bodies, and built-up areas generates complex patterns of vegetation greenness, physiological vigor, and moisture availability that are less apparent in metropolitan-scale analyses. By incorporating a representative zooming area, the study provides additional evidence that multi-index remote sensing approaches are capable of capturing localized vegetation dynamics and landscape variability that may otherwise remain obscured when analyses are conducted solely at broader spatial scales.

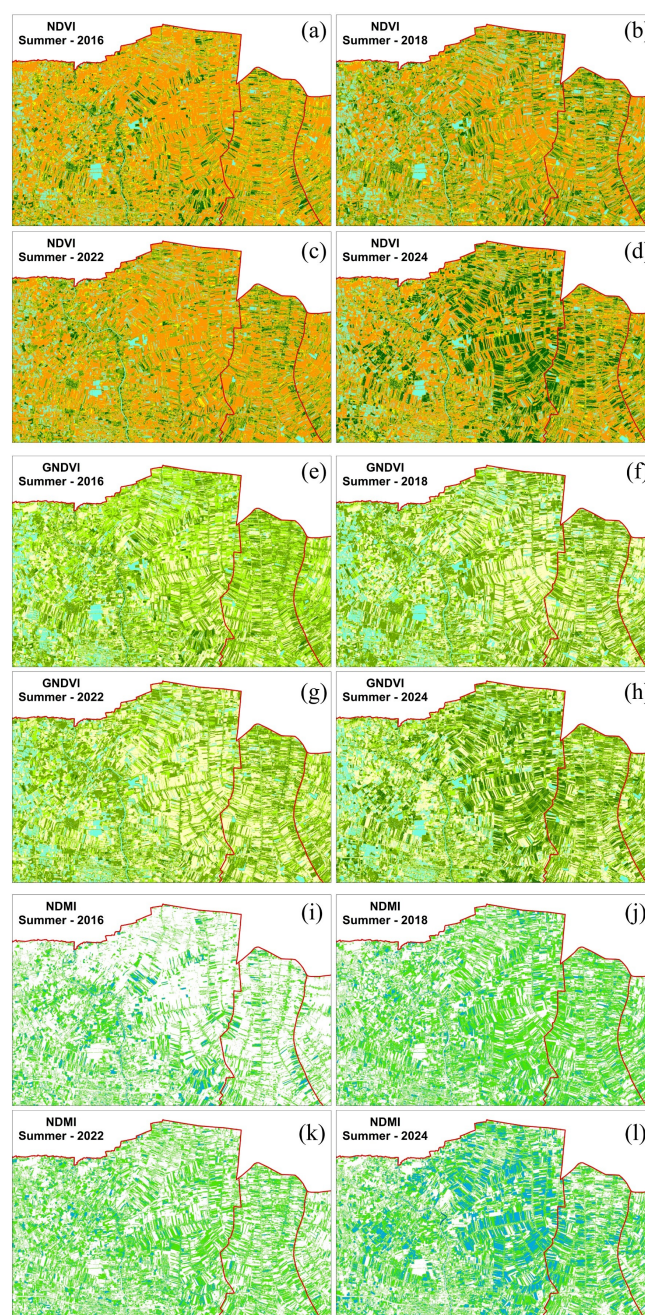


Fig. 7. Local-scale variation of NDVI, GNDVI, and NDMI in the selected zooming area during the summers of 2016, 2018, 2022, and 2024.

V. CONCLUSION

This study examined spatiotemporal patterns of summer urban vegetation greenness and moisture in the Bangkok Metropolitan Region (BMR) using Sentinel-2 imagery and multi-index analysis (NDVI, GNDVI, and NDMI). The results reveal that while average vegetation greenness has remained relatively stable between 2016 and 2024, notable changes in vegetation conditions were observed, including a reduction in areas characterized by relatively dense vegetation and increasing spatial variability, particularly in peri-urban areas.

The analysis further demonstrates a partial decoupling between vegetation greenness and moisture availability, indicating that visually green vegetation does not necessarily reflect healthy or well-watered conditions. Persistent low NDMI values in urban areas highlight the critical role of water availability as a limiting factor for vegetation resilience, even in years with relatively higher rainfall. These findings suggest that differences in land-cover characteristics may influence vegetation structure and moisture conditions, leading to increased vegetation stress under tropical summer conditions.

From an urban ecological perspective, the results indicate a growing reliance on managed green spaces and vegetation maintained under varying moisture conditions, with important implications for ecosystem service provision, particularly urban cooling and climate regulation. Therefore, maintaining average greenness alone is insufficient; urban planning strategies should prioritize vegetation quality, moisture availability, and spatial connectivity to enhance resilience.

Overall, this study highlights the value of integrating multiple remote sensing indices to capture both structural and functional aspects of urban vegetation. Future research should incorporate socio-economic and hydrological data to better understand the drivers of vegetation stress and to support more effective, climate-adaptive urban planning in rapidly urbanizing tropical cities.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

N.P.P. conceived and designed the study, performed data collection and satellite image processing, conducted data analysis and interpretation, and led the writing and revision of the manuscript; P.S. contributed to data interpretation, methodological discussion, and manuscript review; A.Y. assisted with conceptual discussion, interpretation of results, and critical revision of the manuscript; all authors had read and approved the final manuscript.

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