



Mangrove browning trends in the semiarid southern Caribbean: spatial context matters

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ABSTRACT.—Mangroves are tropical coastal ecosystems threatened mainly by land cover change due to commodities. The effect of urbanization has been overlooked due to the low percentage of area loss globally, but it can be a significant driver of mangrove loss locally. Moreover, highly fragmented mangrove areas dominated by small patches might be more sensitive to natural and anthropogenic stressors as in terrestrial forests, especially in highly modified systems such as cities. However, little is known about the interactive effects of these drivers on mangrove loss and degradation, namely urbanization and fragmentation. Our objective is to analyze the mangrove ecosystem's response in terms of the greenness trend to urbanization and patch fragmentation in the semiarid Colombian Caribbean. Specifically, we aim to: (1) calculate the greenness trend from 2017 to 2023 during the dry season by analyzing the normalized difference vegetation index (NDVI) derived from Sentinel-2 satellite images; (2) correlate the greenness trend in mangrove patches with fragmentation metrics at the patch level; (3) evaluate the patch greenness trend along an urban-to-rural gradient. Our analysis revealed that 89.5% of the area showed no significant trend, while 5.2% exhibited greenness trends and 5.3% showed browning trends, mainly concentrated along the Dique channel and the Sinú River delta. Patch shape and isolation did not seem to affect patch greenness trends. In-patch greenness trends variability followed a U-shaped pattern along the urban to rural gradient. These findings highlight the importance of spatial context on vegetation condition and suggest opportunities for remote monitoring of mangrove degradation.

RESUMEN.—Los manglares son ecosistemas costeros tropicales amenazados principalmente por la conversión para la producción de materias primas. A pesar de su baja incidencia global, la urbanización es un impulsor de pérdida a nivel local. Los parches pequeños de manglar podrían ser más



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susceptibles a disturbios naturales y humanos, especialmente en áreas urbanas. Sin embargo, se conoce poco sobre los efectos interactivos de la urbanización y la fragmentación. Nuestro objetivo es analizar la respuesta del manglar, en términos de tendencia de verdor, a la urbanización y el patrón de fragmentación en el Caribe semi-árido colombiano. Nuestros objetivos específicos son: (i) Calcular la tendencia de verdor (2017-2023), durante la temporada seca mediante el análisis del Índice de Vegetación de Diferencia Normalizada (NDVI) derivado de imágenes Sentinel-2; (ii) Correlacionar la tendencia de verdor con métricas de fragmentación a nivel de parche; (iii) Evaluar la tendencia de verdor a lo largo de un gradiente urbano-rural. Nuestro análisis reveló que el 89.5% del área no presenta tendencia en el verdor, mientras que el 5.2% exhibió tendencias positivas y el 5.3% mostró tendencias negativas, principalmente cerca del canal Dique y el delta del río Sinú. La forma y el grado de aislamiento de los parches no influenciaron las tendencias de verdor. La variabilidad de las tendencias de verdor dentro de los parches siguió un patrón en U a lo largo del gradiente urbano-rural. Estos hallazgos destacan la importancia del contexto espacial y sugieren oportunidades para el monitoreo remoto de la degradación de los manglares.

The provision of ecosystem services by mangroves is well-established (Dahdouh-Guebas et al. 2021), and the impact of large-scale conversion has been extensively documented (Goldberg et al. 2020, Hagger et al. 2022). Despite the persistent negative perceptions, increased awareness of the importance of mangrove ecosystems has contributed to a reduction of global mangrove loss rate (Friess et al. 2020), compared to approximately 20 years ago (Duke et al. 2007). Big data and geospatial information have proven invaluable for managing and understanding mangroves by enabling the mapping of mangrove loss and fragmentation (Thomas et al. 2018, Bryan-Brown et al. 2020, Worthington et al. 2020, Bunting et al. 2022). However, the factors behind mangrove degradation (Yando et al. 2021) and health declines, especially when it does not imply area loss, remain an active area of research (Lee et al., 2021).

Significant progress has been made in mapping mangrove health following various disturbances, including oil spills (Lassalle et al. 2023), chilling events and hurricanes (Zhang et al. 2016), and in evaluating ecosystem integrity and mangrove phenology (Younes et al. 2019; Younes et al. 2020). Advances have also been achieved in detecting large-scale mangrove diebacks (Lovelock et al. 2017), species-specific dieback events (Awty-Carroll et al. 2019), and cryptic ecological degradation (Dahdouh-Guebas et al. 2005). The combined use of satellite images and forest inventories has helped to identify mangroves affected by extreme events, shedding light on the connection between human-induced degradation and delayed recovery after such events (Satyanarayana et al. 2017, Tuholske et al. 2017, Walcker et al. 2019, Lima et al. 2023), which has been identified to be a research priority for the future (Dahdouh-Guebas et al. 2022).

Globally, there is a consistent increase in remotely sensed vegetation browning, which refers to a negative trend in satellite-based vegetation indices, as opposed to greening, which indicates a positive trend (Pan et al. 2018, Liu et al. 2023). These trends reflect spectral shifts caused by changes in chlorophyll content, leaf and stem structure, and foliage condition (Liu et al. 2023), signaling potential shifts in vegetation structure, species composition, ecosystem resilience, and early warnings of forest mortality (Rogers et al. 2018, Liu et al. 2019, Smith et al. 2022). However, in mangrove forests, these browning trends have been less pronounced, with the majority of areas showing no significant trends (Ruan et al. 2022, Zhang et al. 2024). The drivers behind the significant greenness trends in mangroves remains a topic of discussion (Cavanaugh et al. 2018, Ruan et al. 2022). Zhang et al. (2024) suggested that the global increase in vegetation greenness is attributable to the CO₂ fertilization effect. Other studies suggested that site-specific characteristics, including urbanization, could potentially influence mangrove health (Tuholske et al. 2017, Vázquez-Lule et al. 2019, Garcés-Ordóñez et al. 2023), aligning with global analyses indicating a mixed response of vegetation greenness trends to urbanization (Esau et al. 2016, Czekajlo et al. 2020, Jin et al. 2020, Li et al. 2020).

In the Caribbean, mangroves have faced intense urbanization, coupled with impacts by altered hydrology, illegal logging, and coastal erosion (Martinuzzi et al. 2009, Blanco-Libreros and Estrada-Urrea 2015, Tuholske et al. 2017, Villate Daza et al. 2020, Garcés-Ordóñez et al. 2023). This has resulted in one of the highest mangrove loss percentages between 1996 and 2020 (Bunting et al. 2022). Moreover, the fragmentation of Caribbean mangroves (Bryan-Brown et al. 2020, Blanco-Libreros and Ramírez-Ruiz 2021) raise concerns about the declining ecological state (Haddad et al. 2015) and its interactions with other landscape-level threats. Notably, urban areas have exhibited fewer and smaller mangrove fragments compared to vegetated areas (Martinuzzi et al. 2009), underscoring the impact of land use on the landscape structure of mangroves. Consequently, the Caribbean provides an ideal setting to investigate the greenness and browning trends of mangroves in and around cities.

This study is centered on the semiarid Colombian Caribbean, aiming to analyze the mangrove ecosystem's response in terms of the greenness trend to urbanization and patch fragmentation metrics using remote sensing tools. To do so, our specific objectives were to: (i) calculate the greenness trend from 2017 to 2023 during the dry season by analyzing the normalized difference vegetation index (NDVI) derived from Sentinel-2 satellite images; (ii) correlate the greenness trend in mangrove patches with fragmentation metrics at the patch level; (iii) evaluate the patch greenness trend along an urban-to-rural gradient, specifically focusing on the city of Cartagena, one of the largest and oldest cities on the Colombian Caribbean coast. We argue that monitoring mangrove greenness and browning trends and gaining insights into the factors driving these changes are essential for effective mangrove ecosystem management, particularly in the face of global changes.

METHODS

STUDY AREA.—The study area is situated in the Southwestern Caribbean marine ecoregion (Spalding et al. 2007) on the semiarid Caribbean coast of Colombia (IDEAM 2014). Stretching from the southern Sierra Nevada de Santa Marta (11°05'40.2"N, 74°13'13.2"W) to the southern Cispatá Bay (8°48'28.1"N, 76°30'12.2"W; Fig. 1A),

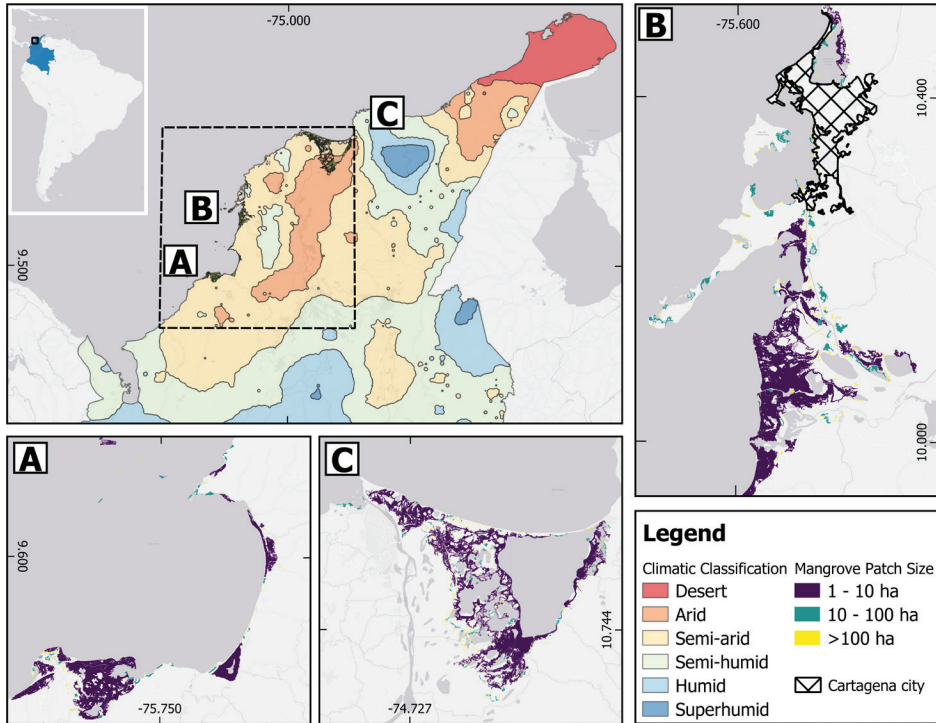


Figure 1. Study area in the semi-arid Colombian Caribbean, according to Lang climatic classification. The panels offer a closer view of the study area, showing patch size class in: (A) Morrosquillo Gulf, in the southern part of the study area, (B) Cartagena (cross-hatched) and Dique Channel in the central part, and (C) Ciénaga Grande de Santa Marta (CGSM) in the northern part of the study area.

the area encompasses 729.34 km² of mangroves predominantly dominated by *Rhizophora* spp., *Avicennia germinans* (L.) L., and *Laguncularia racemosa* (L.) C.F. Gaertn. (Blanco-Libreros et al. 2022). The region experiences a dry season (December–March) and a wet season (August–November), primarily influenced by the Intertropical Convergence Zone (ITCZ; Urrea et al. 2019, Poveda 2023).

Established in 1533, Cartagena stands as the oldest city on the Colombian Caribbean (Fig. 1B), serving as a strategic port since colonial times (Pinzón et al. 2023). Currently, the city hosts port operations, industrial enterprises, tourism, and international trade, with detrimental effects on ecosystems, including pollution, sedimentation and urbanization (Blanco-Libreros and Ramírez-Ruiz 2021, Romero-Murillo et al. 2023). Furthermore, sedimentation in Cartagena Bay and nearby areas, influenced by the Dique Channel—an artificial channel built during colonial times that connects the large Magdalena River with the bay—has increased significantly, particularly over the last three decades (Restrepo et al. 2014, 2017). This historical and geographical context positions Cartagena as an ideal setting for studying the impacts of landscape-scale processes on vegetation dynamics.

QUANTIFYING GREENNESS TREND.—We retrieved all cloud-free Sentinel-2 Level 2A images from Google Earth Engine (GEE) for the dry season (1 January to 30 April) each year from 2016 to 2023 over Colombian mangrove areas (INVEMAR 2022). We

then calculated a median composite from the dry season images each year, resulting in a time series with one composite image representing each year. The dry season was chosen for its typical lack of clouds and its representation of the most stressful period for vegetation in drylands. Additionally, the seasonal variability of vegetation greenness and moisture in our study area is dramatic (Ruiz-Roldán et al. 2023), so using only images from the dry season helps diminish that variability. With the imagery, we calculated the normalized difference vegetation index (NDVI; Huang et al. 2021), which is expressed as:

$$\text{NDVI} = \frac{\text{NIR} - \text{Red}}{\text{NIR} + \text{Red}} \quad \text{Eq. 1}$$

where NIR represents the near-Infrared band (Sentinel-2 Band 8) and Red represents the red band (Sentinel-2 Band 4), both at a 10-m spatial resolution in Sentinel-2 satellite. In mangroves, NDVI has been related to leaf area index (Green et al. 1997), gross primary productivity (Zhang et al. 2022), canopy closure (Jensen et al. 1991), stem density and vegetation stress (Satyanarayana et al. 2011).

To assess the presence of a monotonic temporal trend in NDVI during the dry season from 2018 to 2023, we conducted a Mann–Kendall trend test using the Kendall package (McLeod 2011) in R. The Mann–Kendall (Mann 1945, Kendall 1955) test is a nonparametric test based on Kendall correlation, used to determine if there is a consistent increase or decrease in the variable over time. The null hypothesis is that there is no trend, while the alternative is a significant upward or downward trend. We performed computations on a per-pixel basis (10 × 10 m) to evaluate the NDVI trend and its significance across the time series, with a significance level set at $\alpha = 0.05$. Positive significant trends are referred to as greening, while negative trends are referred to as browning.

Subsequently, we computed the mean NDVI trend and its standard deviation for each mangrove patch using zonal statistics in QGIS (QGIS Development Team 2023), with the official mangrove cartography of Colombia (INVEMAR 2022) used to delimit the patches. Additionally, we calculated the proportion of each patch area exhibiting significant ($P < 0.05$) NDVI trends (no trend, significant positive trend, significant negative trend). In summary, each mangrove patch in the study area was characterized by its mean NDVI trend, standard deviation, and the proportion of the patch with greening, browning, or no trend. The images and code used for the analysis will be accessible following the publication of the research (Ramírez-Ruiz 2024).

EFFECT OF MANGROVE PATCH CHARACTERISTICS ON GREENNESS TREND.—We characterized mangrove patches according to three key patch-scale metrics: patch size, patch isolation (measured using Euclidean nearest-neighbor distance—ENN), and patch shape (using as proxy the perimeter-area ratio—PARA and the fractal dimension index—FRAC; McGarigal 2014). These metrics have helped to understand how spatial patterns influence ecological processes (McGarigal 2014). Smaller patches are more vulnerable to environmental stress due to increased edge effects, exacerbated by complex shapes, while isolated patches face reduced recovery capacity (Haddad et al. 2015). The metrics were calculated using the landscapemetrics package in R (Hesselbarth et al. 2019, R Core Team 2020) over the Colombia’s national mangrove cover layer, derived from 2020 optical and radar imagery at a scale of 1:25,000, as

reported by INVEMAR (2022). Only mangrove patches above 1 ha were included in the analysis.

The relationship between mean and standard deviation for NDVI patch trend and patch isolation and shape, was explored using the Spearman correlation coefficient. For patch size, our analysis involved categorizing the patches into three groups: 1–10 ha, 10–100 ha, and greater than 100 ha. We compared the mean and standard deviation of patch NDVI trends among patch size classes using the Kruskal–Wallis test. If significant differences were found, we conducted pairwise comparisons using the Wilcoxon rank sum test with Bonferroni continuity correction. All statistical analyses were performed using R (R Core Team 2020).

GREENNESS TREND ALONG AN URBAN-RURAL GRADIENT.—To evaluate the influence of proximity to the city on the patch NDVI trend, Cartagena was chosen as a case study. The analysis encompassed the city of Cartagena (IDEAM 2021) and a 40 km buffer around it (Supplementary Fig. S2), as previous research has identified this buffer zone as the area where urbanization notably impacts vegetation greenness (Esau et al. 2016). Generalized Additive Models (GAM) were employed in R (Wood 2017, R Core Team 2020) to determine if there exists a significant relationship between the distance to Cartagena and the mean and standard deviation of the patch trend in NDVI.

RESULTS

GREENNESS TREND.—The semiarid mangroves of the Colombian Caribbean predominantly exhibited a neutral trend in NDVI during the dry seasons from 2017 to 2023, covering 652.87 km² (89.5%) of the mangrove area. Notably, 38.55 km² (5.3%) of mangroves displayed a significant negative NDVI trend, indicating a browning trend, while 37.92 km² (5.2%) of mangrove area exhibited positive NDVI trends, signifying greening.

We identified two areas displaying large spatially continuous (>1.5 km²) browning trends. One area lies adjacent to the Sinú River delta, west of the Cispatá Bay—a protected area with sustainable natural resource use (Fig. 2D). Most of this region falls within the management unit of La Balsa, as outlined in the protected area's management plan (CVS and INVEMAR 2010); henceforth, we will refer to this area as La Balsa. The other region is situated south of the Dique Channel, on the seaward side of El Mono Hernández Cork Forest Flora and Fauna Sanctuary (Fig. 2C), which is a national protected area where tree mortalities have been reported in the freshwater swamp dominated by *Pterocarpus officinalis* Jacq. (Miranda-Castro et al. 2023).

The Ciénega Grande de Santa Marta (CGSM hereafter), one of Colombia's extensively studied mangrove areas and known for significant mangrove mortalities, displays an overall stable NDVI trend (Fig. 2). In our study area, most patches with strong greening trends are concentrated in the internal lagoons of CGSM (Supplementary Fig. S1), while some browning is also evident to the south of the system and near the city of Barranquilla (Fig. 2). Near Cartagena, there are hotspots of browning, particularly in La Virgen Swamp, to the north of the city (Fig. 2B). The remaining mangrove areas have exhibited relatively stable trends in mangrove NDVI.

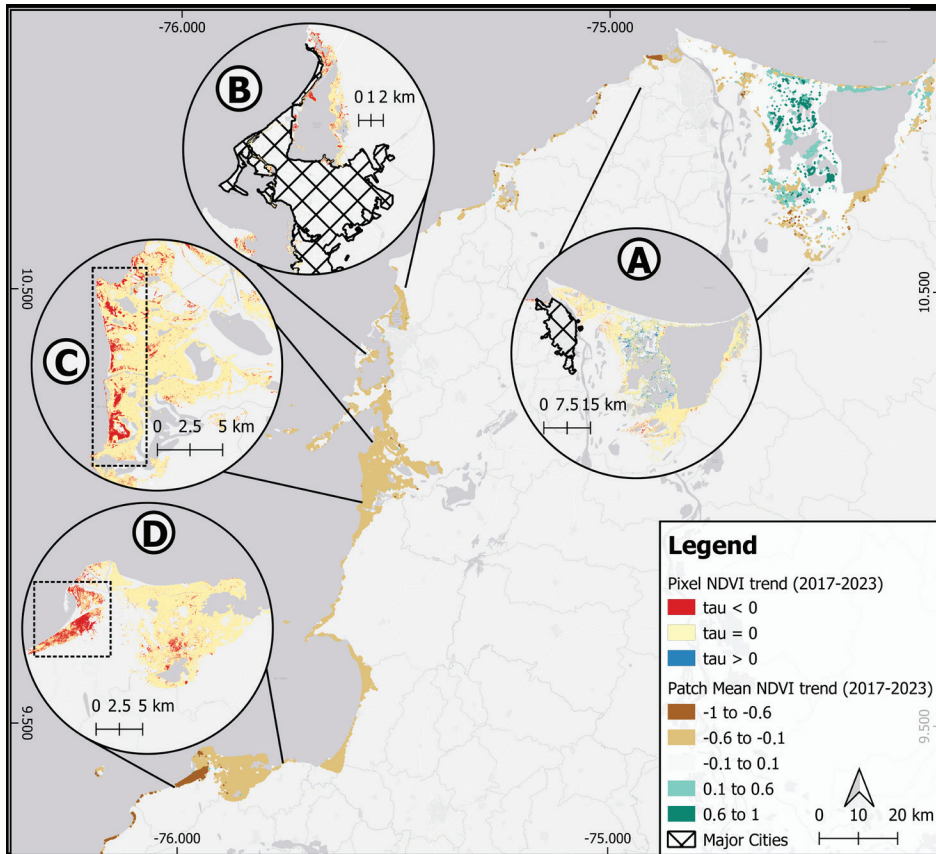


Figure 2. Mangrove greenness (NDVI) Trends (2017–2023) in the semiarid Caribbean coast of Colombia. Geographic distribution of mean patch NDVI trends. Insets show trend values (τ) at the pixel level (10×10 m): (A) Ciénaga Grande de Santa Marta, with Barranquilla city cross-hatched (B) Cartagena City (cross-hatched), located to the north of Dique Channel, (C) El Mono Hernández Cork Forest Flora and Fauna Sanctuary (national protected area), situated to the south of Dique Channel, and (D) Cispatá Bay. Black discontinuous lines highlight two extensive continuous browning areas (>1.5 km²) in panels (C) and (D).

EFFECT OF MANGROVE PATCH CHARACTERISTICS ON GREENNESS TRENDS.— Patch mean NDVI trend did not show a strong correlation ($\rho \leq \pm 0.2$) with ENN, FRAC, or PARA. Similarly, there was no strong correlation between standard deviation of patch NDVI trend and the metrics of patch isolation and shape ($\rho \leq \pm 0.2$). Therefore, we found no strong evidence of an association between patch shape and isolation, with patch greenness trend.

We identified 1102 mangrove patches on the study area, from which 911 are 1–10 ha in size, 161 are 10–100 ha, and 30 patches are greater than 100 ha. The largest mangrove patch is 32.625 ha, located on CGSM (Fig. 1C). Among the patches in the 1–10 ha category, 16.36% of the area shows a significant browning trend, while 8.26% shows a significant greening trend. For patches larger than 100 ha, 9.79% exhibit a significant browning trend, and 5.07% show a significant greening trend. In the 10–100 ha category, 14.93% of the area has a significant browning trend, while 5.3% has a significant greening trend (Fig. 3A).

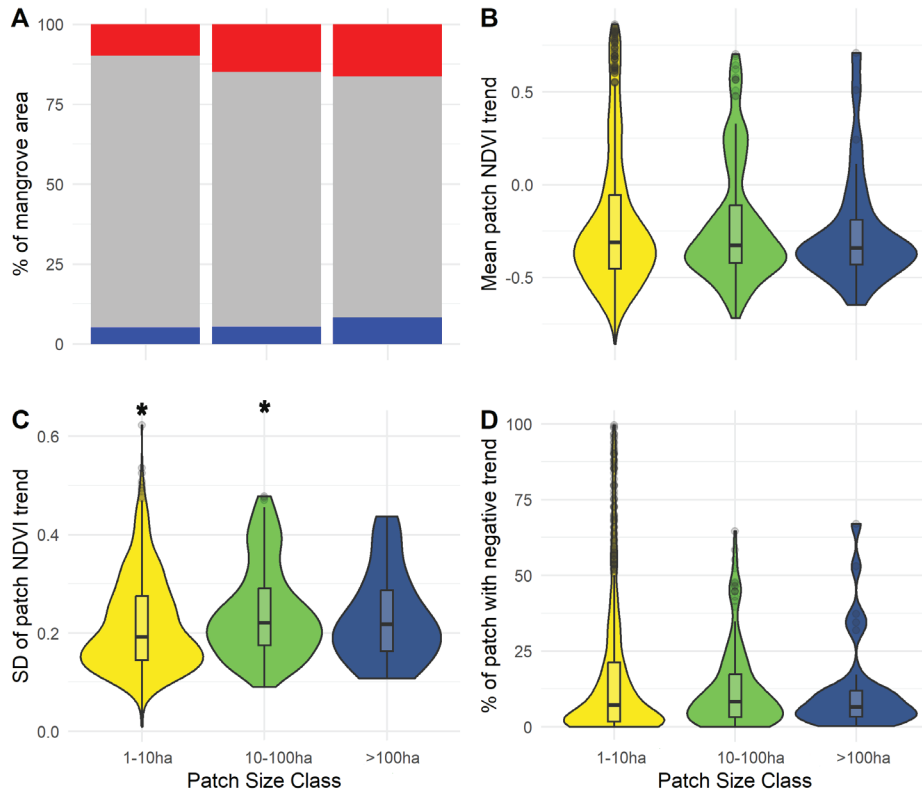


Figure 3. Normalized difference vegetation index (NDVI) trends (2017–2023) in mangrove patches by patch size class. (A) Percentage of pixels with neutral (grey), positive (red), and negative (blue) NDVI trends in each patch size category. (B) Mean NDVI trend in greenness per patch size class. (C) Standard deviation of NDVI trend within patch size categories. Significant differences between 1–10 ha and 10–100 ha patches ($P < 0.01$). (D) Percentage of patch area with significant ($P < 0.05$) negative trend in NDVI.

We found no significant difference in mean patch NDVI trend values (Fig. 3B) among patch size categories ($\chi^2 = 0.32294$, $df = 2$, $P = 0.85$). However, there was a significant difference in standard deviation of patch NDVI trend (Fig. 3C) among patch size categories ($\chi^2 = 11.914$, $df = 2$, $P < 0.01$). There was a significant difference between the 1–10 ha and 10–100 ha categories ($P < 0.01$). Patches in the 1–10 ha category display a wide range of mean trends, from strong greening to strong browning (Fig. 3B). They also exhibit the highest variability in trends within the patch (Fig. 3C) and in the percentage of area experiencing significant browning. Some patches in the 1–10 ha category experience complete browning, whereas patches in the 10–100 ha category and those larger than 100 ha do not exceed 75% of their area undergoing browning (Fig. 3D).

TRENDS ALONG A MAJOR URBAN TO RURAL GRADIENT.—We used Cartagena to test the hypothesis that closeness to the city influences patch greenness trend (Supplementary Fig. S2). We found no significant effect of the distance to city over mean patch NDVI trend ($P > 0.2$). The overall model indicated that only 2.75% of the variability in mean patch NDVI trend was explained by the model (adjusted

$R^2 = 0.015$). However, the proximity to Cartagena influenced the variability in the standard deviation of the patch NDVI trend ($P < 0.01$). Overall, the model explained approximately 16.4% of the variability in standard deviation of NDVI patch trend (adjusted $R^2 = 0.157$), indicating a moderate level of explanatory power. Therefore, proximity to the city seems to influence the inside patch variability in NDVI trend but not the mean patch NDVI trend in our study area.

DISCUSSION

GREENNESS TREND: SPATIAL CONTEXT MATTERS.—Our study suggests a relatively stable NDVI trend in most of the semiarid mangroves of the Colombian Caribbean in the dry season from 2017 to 2023. A relatively small area (<11%) exhibited significant greening or browning trends, contrasting with global estimates that indicate more than one-third of global mangrove areas have significant NDVI trends, mostly positive (Ruan et al. 2022, Zhang et al. 2024). Those global positive trends have been attributed to CO₂ fertilization effect but with high interannual variability due to freshwater availability (Zhang et al. 2024), suggesting mangroves' sensitivity to changes in freshwater input, particularly in arid regions.

The concentration of patches with greening trend at CGSM (Fig. 2A, Supplementary Fig. S1) may be a result of interventions aimed at restoring hydrological connectivity and ongoing reforestation efforts since the 1990s (Rodríguez-Rodríguez et al. 2021, Jaramillo et al. 2024). Despite having one of the largest mangrove mortalities on record, primarily attributed to hypersaline conditions caused by infrastructure hindering hydrologic connectivity, the restoration of CGSM has proven to be relatively successful (Rodríguez-Rodríguez et al. 2021). The CGSM is the most variable area in terms of mean and standard deviation of patch greenness trend (Supplementary Fig. S1).

The two large spatially continuous areas (>1.5 km²) with significant browning trend are concentrated on the margins of big river deltas (Fig. 2). The one located at the seaward side of El Mono Hernández Cork Forest Flora and Fauna Sanctuary is to the south of the Dique Channel. In recent decades, the Magdalena River and its tributaries have experienced increasing trends in sediment load and increased erosion rates, primarily attributed to land use changes and deforestation upstream (Restrepo and Escobar 2018). This surge in sediments and erosion rates has the potential to impact mangrove health in the region, as it has been linked to the loss of vegetation cover and mortality of freshwater swamps in the area (Miranda-Castro et al. 2023). Additionally, it has been associated with the partial disappearance of coral formations and a reduction in the abundance of seagrass beds (Restrepo et al. 2006).

The second area, La Balsa, situated on the western side of the Sinú River delta has been significantly impacted by changes in the delta over the centuries (Castaño et al. 2010). Changes in precipitation and river discharge, influenced by ENSO, have the potential to impact mangrove health in the area (Ruiz-Ochoa et al. 2008). Moreover, the influence of upstream dams, such as Urra I, can further affect freshwater flow, leading to additional alterations in freshwater availability, fluvial sediment transport, and an increase in coastal erosion rates (Ruiz-Ochoa et al. 2008, Rangel-Buitrago et al. 2015). In the management plan, this area has designations for restoration and productive use (CVS and INVEMAR 2010), allowing sustainable forestry. Aquaculture and infrastructure developments are allowed under licenses

from regional environmental authorities. Moreover, the area has been threatened by coconut and rice cultivations (CVS and INVEMAR 2010).

Other studies in arid and semiarid mangrove areas have pointed out that site-specific environmental factors such as the quantity and quality of freshwater input, ocean water exchange, extreme events, and human-induced changes in water flow paths likely impact greenness trends (Vázquez-Lule et al. 2019). This is likely the case in our study area. However, further research is essential to develop a more comprehensive understanding of how the detected NDVI trends correlate with in situ vegetation parameters, including gross primary productivity, canopy closure, and vegetation health. Such investigations will allow us to ascertain whether and how these trends can serve as early-warning indicators of forest degradation.

EFFECT OF PATCH CHARACTERISTICS ON NDVI TREND.—Mangrove fragmentation research has focused in describing fragmentation patterns (Bryan-Brown et al. 2020, Blanco-Libreros and Ramírez-Ruiz 2021, Jaramillo et al. 2023), understanding how management influences fragmentation and ecological condition (Blanco-Libreros and Estrada-Urrea 2015), estimating mangrove population responses (Blanco-Libreros and Ramírez-Ruiz 2021 and references therein), and assessing sensitivity to invasions (Zhang et al. 2021). Less is known about the impact of fragmentation on mangrove ecosystem functioning and resilience, since most of the evidence of fragmentation effects on ecosystem functioning has been gained from long-term experiments in continuous tropical forests, such as the Amazon (Haddad et al. 2015). Yet, the responses of ecosystems with more complex arrangements of patches are harder to elucidate and might require the development of fragmentation metrics tailored to those kinds of ecosystems (Rivas et al. 2022).

We found no strong correlation between patch shape and isolation with the patch NDVI trend. Mangrove patches in the study area are not highly isolated, and mangrove trees are adapted for long-distance dispersal (Van der Stocken et al. 2019). Therefore, patch isolation and shape in our study area might be more the result of natural drivers than a process of anthropogenic interventions, except maybe in highly urbanized areas or agricultural areas (Blanco-Libreros and Estrada-Urrea 2015).

Forest patch size reduction has been linked to shifts in physical environmental changes and has been associated with degradation of ecosystem functions, particularly carbon and nitrogen retention and productivity (Haddad et al. 2015). Additionally, smaller patch size has been related to a higher percentage of forest exhibiting browning (Dias et al. 2022). In our dataset, patch size class showed an impact on inside patch variability in greenness but not on the mean patch trend. On average, patches in the 1–10 ha category exhibit less variability in NDVI trends within the mangrove patch compared to patches in the 10–100 ha category or those larger than 100 ha. However, some patches in the 1–10 ha category may have completely opposite trends in greenness or may be largely homogeneous.

Our findings support recent research emphasizing the conservation value of small patches, which often harbor high biodiversity (Riva and Fahrig 2022) and provide crucial ecosystem services (Curnick et al. 2019). While patch size did not correlate with mean patch NDVI trend, suggesting potential independence of patch size from vegetation conditions, the high variability in vegetation greenness trend observed in smaller patches indicates a significant influence of the surrounding coastalscape on vegetation condition, particularly in smaller patches. This underscores the importance

of considering the broader coastalscape context and spatial configuration of patches for effective conservation strategies.

In the future, improved metrics of anthropogenic-induced fragmentation could provide us with a more comprehensive understanding of the effect of mangrove fragmentation on mangrove ecosystem functioning and health. Furthermore, analyzing how the patch borders behave compared to the core of the patches can also shed light on whether edge effects can be monitored using remote sensing tools.

TRENDS ALONG A MAJOR URBAN TO RURAL GRADIENT.—Cartagena and Barranquilla are the main cities in our study area. The browning trend observed in the Mallorquin swamp, near Barranquilla, is consistent with research suggesting degradation of the mangrove ecosystem due to industrialization and urbanization (Garcés-Ordóñez et al. 2023). Further away from Barranquilla, there is CGSM, but due to its complex disturbance and restoration history, we decided not to use it as a case study to analyze greenness trends along the urban to rural gradient.

Studies in subarctic systems have shown that city vegetation exhibits complex greening-browning sequences depending on the stage of urbanization (Esau et al. 2016). Over the long term, despite background browning trends, city vegetation tends to become greener due to the influence of heat islands (Esau et al. 2016). We did not find a clear trend in the mean patch NDVI trend from Cartagena outwards. The distance to the city influenced the in-patch variability of NDVI trend, with the highest variability in the city core, decreasing up to 30 km away and then increasing again afterwards (Supplementary Fig. S2). Therefore, the mangrove patches with most heterogeneous NDVI pixel trends are found at Cartagena. Further research shedding light on the influence of landscape disturbances on mangrove vegetation condition will enrich our understanding of these patterns.

Mangroves, unlike subarctic systems, are not typically limited by naturally occurring temperature, which means that the positive effects of urban heat islands, if any, are less pronounced. However, they can still be subject to other disturbances associated with urban areas (Branoff 2017). Small-scale disturbances can have both negative and positive effects on vegetation greenness and condition, which may contribute to the more heterogeneous condition of mangrove vegetation in urban areas.

For example, in La Virgen Swamp (Supplementary Fig. S2D), certain areas exhibit stable greenness, while others display a widespread browning trend. This variation is likely attributed to small-scale drivers such as trampling, logging, sedimentation, and other local factors. The consistent browning trend observed in coastal lagoons such as La Virgen Swamp near Cartagena and Mallorquin Swamp near Barranquilla raises questions about the sensitivity of urban coastal lagoons to urbanization. Monitoring the water bodies of these lagoons and implementing additional incentives to protect them are crucial for their persistence, especially considering their vulnerability to interactive threats such as climate change and urbanization.

LIMITATIONS AND FUTURE APPROACH.—We only focused on analyzing monotonic trends in greenness, yet we acknowledge the potential for spurious trends, especially those arising from piecewise trends (e.g., initial greening followed by browning) that may falsely appear as a neutral trend (Cortés et al. 2021). However, due to the relatively short temporal span of our study (6 yr), we anticipate that such trends are

likely not widespread. Nevertheless, future studies could benefit from exploring multiple trends hypotheses, incorporating other spectral indices (Tran et al. 2022, Zhang et al. 2022), and integrating field data into the analyses.

Moreover, studies with higher temporal resolution could help elucidate the relationship between vegetation health and extreme weather events, which is critical in our era of global changes (Dahdouh-Guebas et al. 2022). Notably, the study period began after the 2015–2016 El Niño, which reduced precipitation, followed by the 2020–2023 La Niña conditions, which increased precipitation (Poveda 2023), both potentially affecting vegetation greenness. Although these ENSO cycles were not the focus of this study, longer-term analyses could further reveal their impact on mangrove vegetation.

Particularly, the use of Generalized Additive Models promises to be instrumental in relating phenology to environmental variables such as precipitation and predicting phenological changes (Younes et al. 2020). Furthermore, combining information on net greenness values and greenness trends would enrich our understanding of mangrove vegetation status and health over time, critical for developing early-warning systems that alert declining ecosystem health and functioning (Dahdouh-Guebas et al. 2022).

A more detailed characterization of mangrove patch arrangements, that can better distinguish which patches have been subject to recent human-induced fragmentation processes, and a more precise description of patch edges, would be useful to better understand the effects of fragmentation over ecosystem health and functioning. To better understand fragmentation effects on mangroves, we should acknowledge that edge effects depend on edge identity, recognize that spatial context influences ecosystem health, and acknowledge that ecosystems have time-lagged responses. Additionally, we must recognize the synergistic interactions between fragmentation and other global change drivers (Didham 2010).

Furthermore, the complex interplay between urban environments and adjacent ecosystems requires further investigation. Factors such as agricultural runoff, coastal erosion, and oceanic dynamics can contribute to the spread of urban impacts on coastal ecosystems, including coastal marine pollution, which exhibits a strong spatial spillover effect (Xu and Zhang 2022). Future research should provide spatially explicit descriptions of urbanization intensity to clarify the relationship between urbanization and vegetation health. Expanding the scope of studies to include multiple urban-rural trends would enable us to elucidate how specific urban characteristics influence coastal vegetation dynamics.

Finally, this methodology introduces an innovative approach combining geospatial data and cloud computing to assess changes in vegetation condition. The identified greening and browning trends can guide ground-based research and monitoring, helping to uncover underlying causes and enhance our understanding of mangrove vegetation condition and stressors. When integrated with climate data, spatial characteristics, and phenological observations, this approach has proven effective in detecting forest decline hotspots (Buras et al. 2021). We anticipate that it will be similarly valuable in our study area, particularly in contexts where technical and budgetary constraints limit sampling efforts. Furthermore, this methodology may also be applicable to other regions and ecosystems for monitoring vegetation and understanding how patch characteristics, urbanization, and landscape configuration impact vegetation conditions.

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