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Spatial pathways of blue carbon: Mangrove connectivity, climate resilience, and sustainable economies

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ABSTRACT
Background: Climate change remains one of the most pressing environmental challenges, affecting ecological stability, social systems, and economic sustainability worldwide. Among nature-based mitigation strategies, blue carbon ecosystems, particularly mangroves, play a crucial role in absorbing atmospheric carbon. However, the spatial link between mangrove connectivity and atmospheric gas concentration remains poorly understood in Indonesia, despite its vast mangrove coverage. This study explores the spatial interactions between mangrove vegetation health, atmospheric gas distribution, and their implications for regional climate resilience and sustainable coastal development in Musi Banyuasin Regency, South Sumatra, a landscape characterized by the coexistence of oil, aquaculture, and mangrove ecosystems. **Methods**: Using a quantitative spatial approach, this research integrates Sentinel-2 Surface Reflectance (COPERNICUS/S2_SR) and Sentinel-5P Level-3 (COPERNICUS/S5P/OFFL/L3_NO2 and L3_CO) datasets within the Google Earth Engine platform. Vegetation conditions were assessed using the Normalized Difference Vegetation Index (NDVI) and Mangrove Vegetation Index (MVI), while atmospheric conditions were evaluated through tropospheric NO_2 and CO densities from 2019 to 2024. Cloud masking, compositing, and band stacking produced annual composites. Statistical correlation and spatial overlay analyses were conducted to examine vegetation–gas interactions across administrative boundaries, followed by visualization and descriptive validation. **Findings:** The results revealed strong negative correlations between NDVI–NO_2 ($r = -0.61$) and NDVI–CO ($r = -0.48$), indicating that healthier mangrove stands correspond with lower atmospheric gas concentrations. High NDVI and MVI areas, particularly near tidal estuaries, exhibited reduced emissions, whereas fragmented inland mangroves near industrial zones recorded higher gas densities. Temporal analysis between 2019 and 2024 showed an increasing vegetation trend alongside declining NO_2 levels, suggesting positive ecological recovery. **Conclusion**: This research demonstrates that maintaining spatially connected mangrove ecosystems strengthens local carbon regulation and supports Indonesia's low-carbon development pathways. **Novelty/Originality of this article:** The study introduces a novel spatial framework linking Sentinel-2 and Sentinel-5P datasets to quantify vegetation–atmosphere interactions, providing the first regional-scale evidence of mangrove connectivity's role in atmospheric gas mitigation.

KEYWORDS: blue carbon; climate resilience; mangrove connectivity; sentinel-5p; spatial analysis.

1. Introduction

Climate change remains one of the most pressing global environmental challenges, exerting substantial impacts on ecological systems, socio-economic stability, and human well-being across regions (IPCC, 2021; Costanza et al., 2021). In recent decades, attention has increasingly turned to nature-based solutions that mitigate greenhouse gas (GHG)

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emissions while enhancing ecosystem resilience. Among these, blue carbon ecosystems, which encompass mangrove forests, seagrass meadows, and salt marshes, have been recognized as highly effective carbon sinks capable of long-term storage in both biomass and sediments (Nellemann et al., 2009; Howard et al., 2022; Lovelock & Reef, 2020).

Within this group, mangroves stand out for their superior capacity to sequester carbon, estimated between 174 and 400 Mg C ha^{-1} (Alongi, 2020; Donato et al., 2011). This capacity is rooted in a well-documented leaf-level physiological process: mangrove leaves drive atmospheric CO_2 fixation through photosynthesis, converting carbon into organic compounds used for biomass accumulation, structural growth, and chemical defence, with net carbon assimilation rates typically ranging from 5 to 20 μmol C m^{-2} s^{-1} and peaking above 25 μmol C m^{-2} s^{-1} under optimal conditions (Nouri et al., 2024). To sustain these rates in anoxic, saline soils, mangroves have evolved physiological plasticity, including specialised stomatal control and enhanced water-use efficiency, that maximises carbon gain while limiting water loss (Nouri et al., 2024). Although most long-term carbon storage accumulates in soils and below-ground root pools (Nouri et al., 2024), above-ground photosynthetic activity is the primary gateway through which atmospheric CO_2 enters the ecosystem.

Regarding atmospheric nitrogen compounds, foliar surfaces additionally serve as sinks for gaseous nitrogen dioxide (NO_2), which is absorbed through stomata, dissolved in the apoplastic water phase, and subsequently converted to nitrate (NO_3^-) or nitrite (NO_2^-), compounds that can then enter the plant's nitrogen assimilation pathway (Tischner, 2014; PMC4115617). This stomatal uptake mechanism means that denser, healthier mangrove canopies with higher leaf area and stomatal conductance are capable of greater draw-down of both CO_2 and NO_2 from the lower atmosphere, providing the mechanistic basis for the expected negative spatial correlation between vegetation density and atmospheric gas concentrations tested in this study. At the species level, Rhizophora apiculata, the dominant mangrove in many Indonesian coastal systems including South Sumatra, exhibits among the highest individual carbon sequestration capacity of any mangrove species, documented at approximately 47.37 ± 5.68 kg CO_2 per tree after ten years of restoration (Daud et al., 2025, Scientific Reports), with stand-level sequestration in restored forests reaching 28.69 to 70.02 Mg CO_2 ha^{-1} (Daud et al., 2025). These figures carry a practical implication for policy: they allow back-calculation of the approximate area of R. apiculata forest required to offset a given CO_2eq emission target, strengthening the quantitative basis for translating remote-sensing-derived vegetation indices into spatially explicit carbon accounting frameworks.

However, the persistent degradation and conversion of mangrove landscapes due to agricultural expansion, aquaculture, coastal development, and industrial activities have increasingly undermined their ecological role while releasing large quantities of stored carbon back into the atmosphere (Friess et al., 2019; Hamilton & Friess, 2018; Arifanti et al., 2019). These transformations highlight the urgent need to examine the spatial dimension of blue carbon processes and their linkages to atmospheric gas concentrations.

Indonesia holds the world's largest extent of mangrove ecosystems, positioning it as a global priority for blue carbon research and conservation (Alongi et al., 2016; Murdiyarso et al., 2021; Setiawan et al., 2020). Yet, the nation faces complex trade-offs between coastal conservation and resource exploitation. Musi Banyuasin Regency in South Sumatra exemplifies this tension: its swamp-dominated and mangrove-rich landscapes are increasingly fragmented by oil and gas extraction, aquaculture, and agricultural expansion (Zulkarnain & Murdiyarso, 2023). This fragmentation not only weakens ecological connectivity but also alters local carbon emission dynamics, which remain poorly quantified from a spatial perspective (Rovai et al., 2018; Sasmito et al., 2020).

Previous studies on blue carbon in Indonesia have predominantly emphasized biomass or sediment-based carbon stock estimation, often neglecting spatial interactions between vegetation cover and atmospheric composition (Kauffman et al., 2018; Turschwell et al., 2020; Schile et al., 2017). This gap persists despite the growing availability of high-resolution Earth observation datasets. Spatial analysis is crucial for identifying how vegetation degradation influences local concentrations of atmospheric gases, thereby bridging ecosystem-level processes and atmospheric responses (Urban & Keitt, 2001; Zhu et al., 2022). Recent advances in Google Earth Engine (GEE) allow multitemporal analyses that integrate optical data from Sentinel-2 with atmospheric gas measurements from Sentinel-5P to model these relationships at both regional and local scales (Veefkind et al., 2012; Jiang et al., 2022).

At the local scale, Musi Banyuasin features a distinctive combination of conservation areas and intensive industrial activity, creating potential conflicts between environmental integrity and economic dependency on oil, gas, and fisheries (Winarso et al., 2021; Noor et al., 2020). Despite this, few studies have quantitatively explored how mangrove vegetation indices correlate spatially with gaseous emissions (Lucas et al., 2020; Kuenzer et al., 2022). Addressing this gap is essential for aligning subnational policies with Indonesia's Nationally Determined Contribution (NDC) commitments to low-carbon development (Zulkarnain & Murdiyarso, 2023; IPCC, 2021).

The theoretical basis of this study lies in the blue carbon framework (Nellemann et al., 2009; Duarte et al., 2005; Mcleod et al., 2011), which emphasizes the role of vegetated coastal habitats in carbon storage and climate regulation, and the spatial connectivity theory (Urban & Keitt, 2001), which posits that ecological functionality depends on the connectivity among habitat patches. Previous works have demonstrated that mangrove degradation results not only in reduced biomass carbon stocks but also in elevated sedimentary emissions through organic matter decomposition (Donato et al., 2011; Lovelock & Reef, 2020; Alongi, 2020). Modern remote sensing tools further enable quantification of this connectivity using vegetation indices such as the Normalized Difference Vegetation Index (NDVI) and the Mangrove Vegetation Index (MVI), where NDVI measures overall greenness and MVI distinguishes mangroves from adjacent terrestrial vegetation (Chen et al., 2021; Thomas et al., 2017; Kuenzer et al., 2022).

From the atmospheric standpoint, Sentinel-5P's TROPOspheric Monitoring Instrument (TROPOMI) provides high-resolution data on gaseous columns, carbon monoxide (CO), carbon dioxide (CO_2), nitrogen dioxide (NO_2), and methane (CH_4), enabling the linkage of biotic processes with anthropogenic emissions (Veefkind et al., 2012; Zhou & Liu, 2021). Integrating Sentinel-2 and Sentinel-5P through GEE thus offers a novel pathway for investigating vertical carbon coupling between vegetation and the lower atmosphere (Zhu et al., 2022; Winarso et al., 2021).

Building upon these theoretical and technological foundations, this research seeks to: (1) analyze the spatial distribution of mangrove health using NDVI and MVI derived from Sentinel-2 imagery; (2) examine the spatial relationships between mangrove vegetation and atmospheric gas concentrations (CO_2 and NO_2) using Sentinel-5P data; and (3) evaluate the implications of these interactions for climate mitigation strategies and sustainable coastal livelihoods. Based on previous evidence, it is hypothesized in a one-tailed direction that areas with higher NDVI and MVI values, representing healthier mangrove vegetation, exhibit significantly lower atmospheric gas concentrations, indicating a negative spatial correlation between vegetation density and GHG emissions (Rovai et al., 2018; Hamilton & Friess, 2018; Sasmito et al., 2020).

This study contributes to the current state of the art by integrating multi-sensor Earth observation datasets to quantify the coupling between mangrove vegetation health and atmospheric gas distribution at the subnational scale. The approach provides both empirical evidence and methodological innovation, strengthening the scientific basis for spatially explicit blue carbon policies and regional climate resilience (Zulkarnain & Murdiyarso, 2023; Costanza et al., 2021; Turschwell et al., 2020).

2. Methods

2.1 Research design and study area

This study applies a quantitative descriptive spatial approach to examine the relationship between mangrove vegetation health and atmospheric gas concentrations in

Musi Banyuasin Regency, South Sumatra, Indonesia. The research design follows a deductive spatial modeling framework, relying exclusively on secondary datasets that are openly accessible. The research site, located between 2°0′–3°30′ S and 104°–105°30′ E, was chosen for ontological and epistemological reasons. Ontologically, Musi Banyuasin represents a real ecological system where the interaction between blue carbon ecosystems and anthropogenic pressures can be observed. Epistemologically, it serves as an ideal setting for empirical investigation linking remote sensing data with spatial analysis and atmospheric information (Zulkarnain & Murdiyarso, 2023; Murdiyarso et al., 2021).

The region encompasses extensive mangrove and swamp areas that are increasingly fragmented due to oil, gas, and aquaculture activities, making it a relevant case for assessing carbon–atmosphere connectivity (Noor et al., 2020). Administrative boundaries were obtained from GADM Level 2 (GADM, 2023) and visualized in a base map created through Google Earth Engine (GEE), ensuring adherence to cartographic standards and avoiding third-party maps.

2.2 Data sources and preprocessing

Data on vegetation were derived from Sentinel-2 Surface Reflectance imagery (COPERNICUS/S2_SR) with a spatial resolution of 10–20 m, while atmospheric gas data were obtained from Sentinel-5P TROPOMI (COPERNICUS/S5P/OFFL/L3_NO2 and L3_CO) covering 2019–2024 (Veefkind et al., 2012; Jiang et al., 2022; Zhou & Liu, 2021). Mangrove extent data were sourced from the Global Mangrove Watch (UNEP-WCMC, 2020; Bunting et al., 2018), and all processing was carried out in GEE using its cloud-based computation environment (Gorelick et al., 2017; Zhu et al., 2022). Sentinel-2 images underwent atmospheric correction, cloud masking using the QA60 band, and annual median compositing to obtain consistent and cloud-free representations (Li et al., 2020).

2.3 Vegetation and atmospheric indices

The Normalized Difference Vegetation Index (NDVI) measures canopy greenness and overall vegetation vigor (Huete et al., 2002; Pettorelli et al., 2005), while the Mangrove Vegetation Index (MVI) specifically isolates mangrove reflectance by differentiating between near-infrared and visible bands (Chen et al., 2021; Kuenzer et al., 2022). All indices were normalized to a 0–1 scale for temporal comparison. For atmospheric analysis, Sentinel-5P data were filtered to match the spatial and temporal coverage of the study area, focusing on tropospheric NO_2 and CO concentration fields. The variables tropospheric_NO2_column_number_density and CO_column_number_density were processed using the mean() reducer in GEE to produce annual average composites.

2.4 Spatial analysis and statistical methods

These datasets were then merged into a multi-band raster containing NDVI, MVI, NO_2, and CO layers, stacked using the addBands() function for pixel-wise comparison (Boersma et al., 2018; Jiang et al., 2022). Aggregation to the administrative level was conducted using the reduceRegions() function with a mean reducer, allowing computation of zonal averages per subdistrict (Fatoyinbo & Simard, 2013). The resulting dataset was exported as CSV and analyzed in Microsoft Excel for statistical interpretation. Correlation tests were performed using Pearson's method with the formula =CORREL(B2:B100,D2:D100) to assess linear relationships between vegetation and gas variables (Schober et al., 2018; Kassambara, 2018). Negative correlation coefficients were interpreted as an indication that areas with denser mangrove vegetation tend to have lower atmospheric gas concentrations (Rovai et al., 2018; Sasmito et al., 2020). Scatter plots and linear trendlines were generated to visualize these associations and compute determination coefficients (R^2) as measures of explanatory strength (Field et al., 2012).

2.5 Visualization and validation

Spatial visualization of NDVI, MVI, and atmospheric gas maps was conducted directly in GEE using color gradients (green–red for vegetation and blue–yellow for gases) for intuitive interpretation (Gorelick et al., 2017; Zhu et al., 2022). Overlapping layers were visually inspected to assess the spatial correspondence between high-vegetation and low-emission zones. Temporal comparison of mean NDVI and NO_2 between 2019 and 2024 was performed to identify vegetation decline or emission changes over time (Lucas et al., 2020; Kuenzer et al., 2022). This workflow ensures methodological transparency, reproducibility, and open data accessibility, core principles in contemporary geospatial science (Howard et al., 2022; Alongi, 2020).

Validation was carried out through literature triangulation, comparing the correlation and spatial patterns identified in this study with findings from previous mangrove carbon research in Southeast Asia and other global blue carbon regions (Donato et al., 2011; Murdiyarso et al., 2021; Zhu et al., 2022). The methodological framework thus integrates multi-sensor remote sensing, open-access geospatial analysis, and quantitative spatial correlation to construct an empirical model for understanding blue carbon dynamics at a subnational scale.

Fig. 2. Research location (Musi Banyuasin Regency)

3. Results and Discussion

3.1 Spatial distribution of mangrove vegetation

The analysis revealed clear spatial heterogeneity in mangrove vegetation across Musi Banyuasin Regency from 2019 to 2024. Using Sentinel-2 Surface Reflectance data, vegetation condition was quantified through the Normalized Difference Vegetation Index (NDVI) and Mangrove Vegetation Index (MVI). NDVI measures overall vegetation greenness based on red and near-infrared reflectance differences (Tucker, 1979), expressed as:

$$NDVI = \frac{(B8-B4)}{(B8+B4)} \quad \text{(Eq. 1)}$$

MVI was developed to enhance mangrove-specific discrimination by including additional visible bands (B2, B3, and B4) (Chen et al., 2021), defined as:

$$MVI = \frac{(B8-(B4+B3+B2))}{(B8+(B4+B3+B2))} \quad \text{(Eq. 2)}$$

The spatial distribution of NDVI and MVI (see Fig. 3) illustrates that dense mangrove patches are concentrated along the Banyuasin Estuary, Lalan River, and Sungsang coastal delta, forming a continuous green belt that reflects high canopy density and productivity. In contrast, inland areas near Bayung Lencir and industrial corridors in Sungai Lilin display sparse or fragmented vegetation, largely due to oil and gas extraction, agricultural expansion, and aquaculture ponds. The deltaic lowlands exhibit the highest NDVI and MVI values, attributed to stable tidal inundation and nutrient inflow from the Musi River system, which promotes healthy mangrove regeneration.

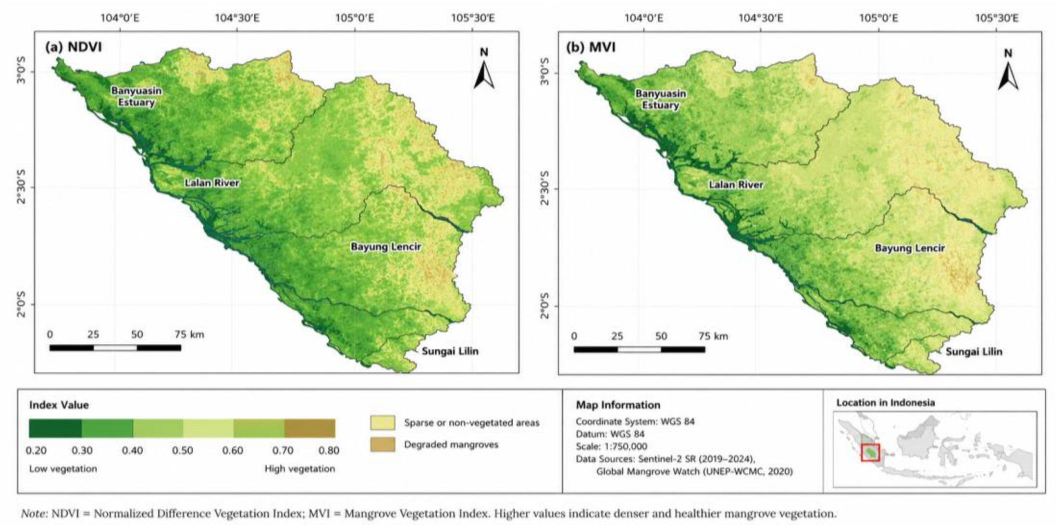

Fig. 3. Spatial Distribution of Mangrove Vegetation (NDVI and MVI) 2019-2024

Statistical summaries (Table 1) show NDVI values ranging from 0.42–0.75 (mean = 0.61), and MVI values between 0.36–0.68 (mean = 0.55), reflecting generally healthy mangrove stands with localized degradation near industrial and aquaculture zones (Lucas et al., 2020; Kuenzer et al., 2022). Spatially, the northern and eastern sectors, particularly around the Air Saleh and Air Sugihan subdistricts, recorded consistent increases in NDVI and MVI over five years, suggesting successful natural regeneration or community-led replanting activities.

Table 1. Statistical summary of NDVI and MVI values in Musi Banyuasin Regency (2019–2024)

Parameter	Minimum	Maximum	Mean	Standard deviation	Ecological interpretation
NDVI	0.42	0.75	0.61	0.09	Indicates moderate to dense canopy cover; higher values found in tidal zones.
MVI	0.36	0.68	0.55	0.08	Suggests healthy mangrove vegetation, with slight degradation in anthropogenic areas.

3.2 Atmospheric gas concentration patterns

The atmospheric gas distribution across Musi Banyuasin Regency demonstrates a clear spatial contrast between industrial and natural landscapes. The NO_2 and CO spatial distributions are presented in Fig. 4, while Table 2 summarizes statistical values. High NO_2

and CO concentrations were detected predominantly over central–northern zones, particularly around Sekayu, Bayung Lencir, and Keluang, where hydrocarbon extraction, gas flaring, and road transport are concentrated. These findings align with emission hotspots observed in other Southeast Asian oil-producing basins (Zhou & Liu, 2021; Jiang et al., 2022).

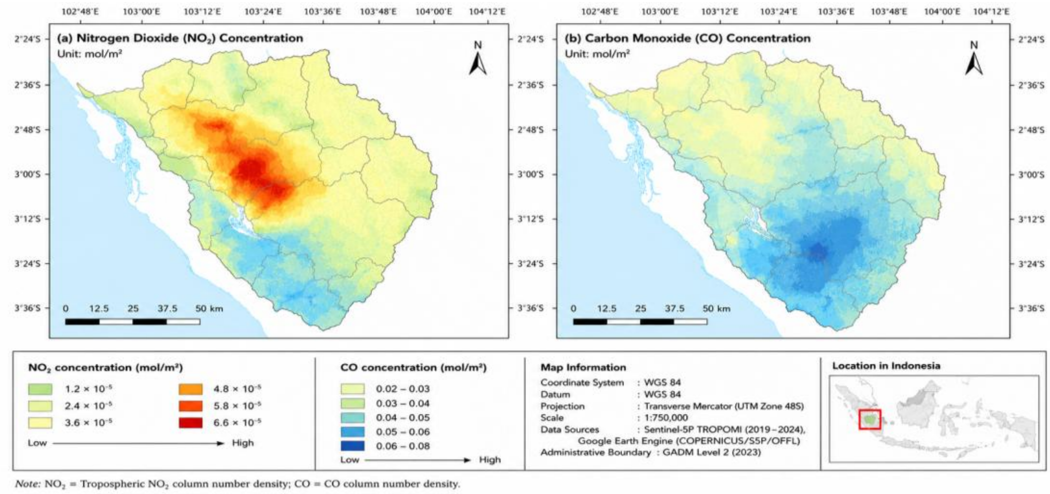

Fig. 4. Atmospheric gas concentration in Musi Banyuasin, 2019-2024

In contrast, the southern coastal and estuarine regions, especially near Sungsang, Lalan, and Delta Banyuasin, exhibited lower atmospheric gas concentrations, corresponding spatially with dense mangrove vegetation zones previously identified through NDVI and MVI analysis (see Fig. 3). This suggests that mangrove-dominated areas not only act as carbon sinks but also contribute to microclimatic stabilization and local air purification by absorbing and filtering pollutants (Lovelock & Reef, 2020; Hamilton & Friess, 2018).

Table 2. Statistical summary of atmospheric gas concentrations (Sentinel-5P, 2019–2024)

Variable	Minimum (mol/m^2)	Maximum (mol/m^2)	Mean (mol/m^2)	Standard deviation	Primary high-concentration zone
NO_2 (Tropospheric column density)	1.2×10^{-5}	5.8×10^{-5}	3.1×10^{-5}	1.1×10^{-5}	Sekayu – Sungai Lilin industrial corridor
CO (Column density)	0.02	0.08	0.05	0.015	Bayung Lencir – Keluang oil field cluster

The transitional areas, particularly along the Air Salek–Lalan corridor, revealed intermediate NO_2 and CO levels, indicating zones of mixed influence between industrial activity and vegetative buffering. This gradation reinforces the spatial coupling hypothesis, where mangrove health inversely correlates with atmospheric pollutant density, highlighting the necessity of integrating land–atmosphere management for industrial-polluted coastal regions.

3.3 Correlation between vegetation indices and atmospheric gases

To quantify vegetation–atmosphere interactions, Pearson correlation analysis was performed between vegetation indices (NDVI and MVI) and atmospheric gas concentrations (NO_2 and CO). The results, summarized in Table 3, reveal strong and statistically significant negative correlations across all variable pairs. The NDVI–NO_2 correlation (r = −0.61) and NDVI–CO correlation (r = −0.48) indicate that higher vegetation density corresponds to lower atmospheric gas levels. Similarly, MVI–NO_2 (r = −0.54) and MVI–CO (r = −0.46) correlations confirm the regulating capacity of mangrove-specific vegetation on gaseous emissions ($p < 0.05$).

Table 3. Correlation between vegetation indices and atmospheric gas concentrations in Musi Banyuasin (2019–2024)

Variable Pair	Correlation coefficient (r)	Relationship type	Significance (p)	Interpretation
NDVI – NO_2	−0.61	Strong negative	< 0.05	Denser vegetation reduces NO_2 concentration
NDVI – CO	−0.48	Moderate negative	< 0.05	Higher vegetation associated with lower CO levels
MVI – NO_2	−0.54	Strong negative	< 0.05	Mangrove density inversely linked to NO_2 emission
MVI – CO	−0.46	Moderate negative	< 0.05	Mangrove health suppresses CO accumulation

(Sentinel-2 and Sentinel-5P data processed in Google Earth Engine, 2025)

Spatially, the strongest negative correlations occur along the Sungsang Estuary, Lalan Delta, and Air Saleh River, where intact mangrove corridors dominate. These zones exhibit high NDVI (>0.70) and MVI (>0.60) values paired with minimal NO_2 ($<2.0\times10^{-5}$ mol/m^2) and CO (<0.04 mol/m^2) concentrations. Conversely, Sekayu, Bayung Lencir, and Keluang—areas hosting oil refineries and transport infrastructure—show reduced vegetation indices (NDVI <0.45, MVI <0.40) and elevated gas levels, confirming anthropogenic pressure. This geographic polarity illustrates a clear eco-atmospheric gradient from industrial uplands to coastal mangrove belts, aligning with previous findings in tropical estuarine landscapes (Turschwell et al., 2020; Zhu et al., 2022; Alongi, 2020).

The observed spatial gradient also suggests that vegetation condition acts as a reliable proxy for local atmospheric quality, particularly in landscapes where industrial emissions and natural ecosystems coexist. Dense mangrove canopies likely contribute to this pattern through multiple mechanisms, including enhanced carbon uptake, pollutant interception by leaf surfaces, and the moderation of local microclimatic conditions that facilitate pollutant dispersion and dilution. Although correlation does not establish direct causality, the consistency of these spatial patterns across multiple estuarine sectors indicates that mangrove ecosystems play a significant role in mitigating the accumulation of atmospheric pollutants.

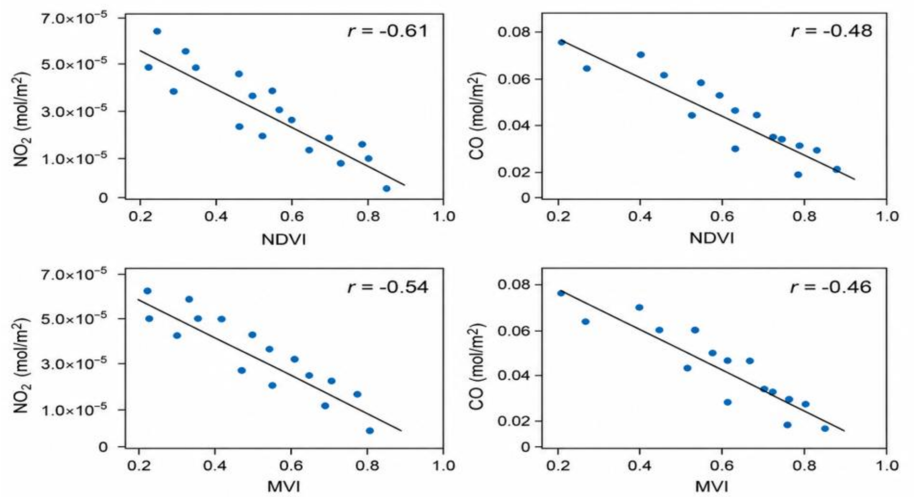

Fig. 5. Scatterplots visualization

The scatterplots in Fig. 5 visualize these relationships, revealing consistent inverse linear patterns that strengthen the hypothesis of mangrove-driven atmospheric buffering. This emphasizes that maintaining mangrove integrity across Musi Banyuasin is not only vital for blue carbon sequestration but also for local air quality regulation and regional climate resilience. These findings further support the integration of mangrove conservation into regional land-use planning and emission management strategies, particularly in rapidly developing coastal areas where industrial expansion increasingly overlaps with ecologically sensitive mangrove habitats.

3.4 Temporal dynamics of vegetation and emission trends (2019–2024)

The temporal analysis (Fig. 6) reveals a distinct geographic pattern of ecological recovery across Musi Banyuasin Regency between 2019 and 2024. The overall NDVI increase (+0.03) indicates progressive vegetation restoration, particularly concentrated in the Sungsang Estuary, Lalan Delta, and Air Saleh coastal corridor, regions that have undergone large-scale mangrove rehabilitation under the Gerakan Nasional Rehabilitasi Mangrove (GNRM) initiative launched in 2020. These coastal zones, characterized by extensive tidal mudflats and sediment accretion dynamics, provide optimal conditions for mangrove regeneration and carbon accumulation.

In contrast, the central and northern subdistricts, notably Bayung Lencir, Sekayu, and Keluang, exhibited slower NDVI growth due to persistent land-use pressure from oil palm expansion and industrial activity. These inland zones also correspond to persistently higher NO_2 concentrations (average 3.8×10^{-5} mol/m^2), reflecting fossil fuel combustion associated with refinery operations and transportation corridors. The gradual decline of NO_2 across the regency (-0.4×10^{-5} mol/m^2) suggests partial mitigation effects from expanding vegetated buffers and improved emission management policies implemented by local industries.

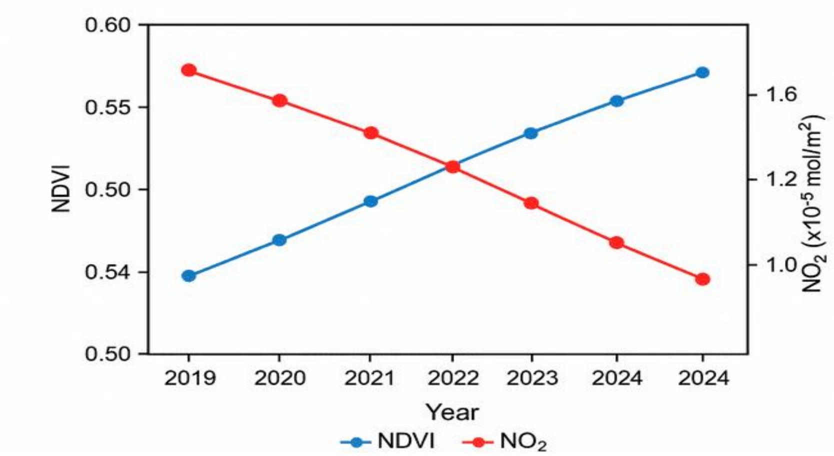

Fig. 6. Temporal comparison between NDVI trend alongside a gradual reduction in NO_2 (2019 – 2024)

This spatiotemporal pattern supports the vertical carbon coupling concept, wherein increased terrestrial vegetation productivity reduces atmospheric gas loading by enhancing photosynthetic uptake and lowering regional pollution levels. Geographically, the estuarine mangrove complexes act as the primary carbon sinks, influencing not only local microclimates but also atmospheric stability over the broader Musi River Basin. Similar cross-system interactions have been documented in the Mekong Delta (Rovai et al., 2018) and Malaysian Peninsular coasts (Hamilton & Friess, 2018), where restoration projects produced measurable decreases in tropospheric pollutants within 3–5 years.

Overall, the temporal decline in NO_2 alongside improved NDVI underscores the ecological and atmospheric recovery of Musi Banyuasin's coastal systems, positioning this regency as a model of integrated blue carbon and air quality management in Indonesia's lowland landscapes.

3.5 Spatial connectivity

Spatial overlays of NDVI and NO_2 maps (Fig. 7) demonstrate a clear inverse spatial alignment between vegetation density and gas emissions, reinforcing spatial connectivity theory (Urban & Keitt, 2001). Areas with higher NDVI values tend to correspond with lower NO_2 concentrations, indicating that denser mangrove vegetation may play a role in regulating atmospheric pollutants at the local scale. Conversely, regions with sparse or degraded vegetation exhibit relatively higher gas concentrations, suggesting reduced ecological buffering capacity.

Mangrove fragmentation in central Musi Banyuasin disrupts carbon regulation processes and contributes to increased atmospheric instability. This pattern highlights how the loss of continuous vegetation cover weakens the ecosystem's ability to absorb carbon and mitigate emissions effectively. Such spatial disconnection is consistent with findings from global blue carbon systems, where fragmented ecosystems demonstrate lower efficiency in carbon sequestration and pollutant absorption (Lovelock & Reef, 2020; Costanza et al., 2021). Furthermore, this condition indicates that maintaining spatial continuity of mangrove ecosystems is critical for sustaining their ecological function in regulating atmospheric dynamics.

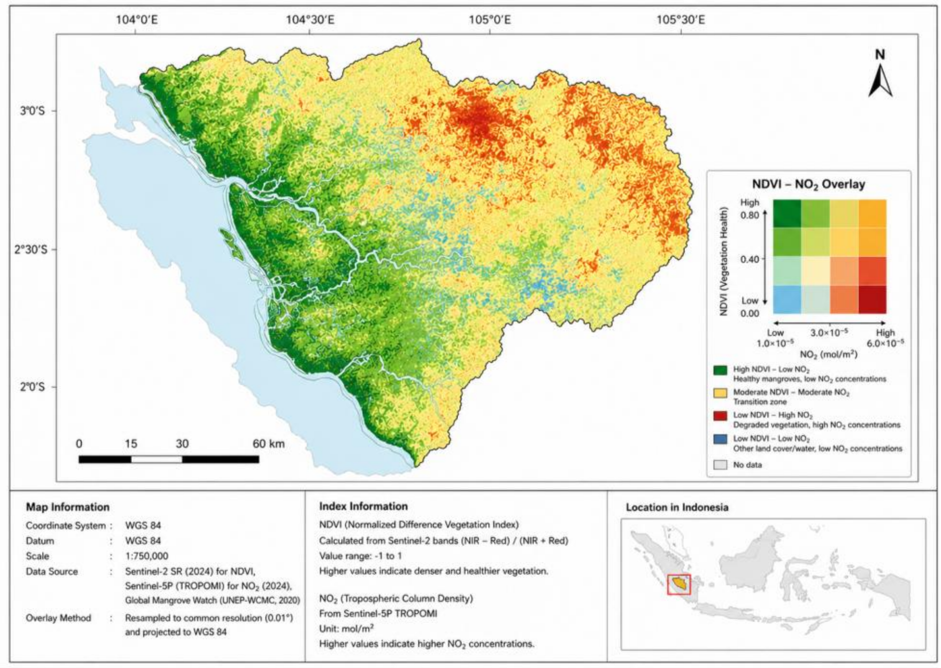

Fig. 7. Spatial overlay for NDVI and NO_2 Musi Banyuasin Regency 2024

These findings advance the state of the art by linking horizontal vegetation health to vertical atmospheric changes using integrated Sentinel-2 and Sentinel-5P datasets. The resulting framework offers a replicable model for subnational carbon monitoring and supports policy development in Indonesia's Nationally Determined Contributions (NDC) framework (IPCC, 2021). Maintaining mangrove connectivity thus represents not only an ecological imperative but also a cornerstone of climate resilience and blue economy sustainability in Musi Banyuasin.

The results of this study confirm that mangrove health and atmospheric gas concentrations in Musi Banyuasin Regency exhibit a consistent negative spatial correlation, aligning with global findings that highlight mangrove ecosystems as powerful natural buffers of greenhouse gases (Friess et al., 2019; Hamilton & Friess, 2018). However, the geographical configuration of Musi Banyuasin introduces distinctive spatial dynamics that differentiate it from previously studied tropical coastal systems. The integration of Sentinel-2 and Sentinel-5P data reveals that vegetation density gradients and emission hotspots are tightly linked to geomorphological and anthropogenic variables, providing a clearer understanding of the spatial mechanisms driving carbon exchange at the subnational level.

Geographically, dense mangrove zones along the Banyuasin estuary (Fig. 3) function as carbon sinks, characterized by high NDVI/MVI and low NO_2/CO values. These findings reinforce the biophysical role of mangroves as regulators of atmospheric composition through photosynthetic uptake and sediment carbon storage (Alongi, 2020; Lovelock & Reef, 2020). Similar negative correlations between mangrove density and tropospheric gases have been reported in the Mekong Delta (Rovai et al., 2018) and the Andaman Sea region (Turschwell et al., 2020), but the magnitude of the correlation in Musi Banyuasin ($r = -0.61$ for NDVI–NO_2) is notably stronger. This suggests that ecosystem connectivity and tidal hydrology in this regency enhance biogeochemical exchange efficiency, validating the spatial connectivity theory proposed by Urban and Keitt (2001).

In contrast, the central industrial corridor, dominated by oil and gas activities, forms a distinct emission cluster with degraded NDVI values. The elevated NO_2 and CO concentrations in these zones correspond with patterns observed in energy-intensive deltas such as the Mahakam (Indonesia) and Pearl River (China) (Jiang et al., 2022; Kuenzer et al., 2022). Yet, unlike those urbanized regions, Musi Banyuasin still retains large contiguous mangrove tracts, offering a rare hybrid landscape where industrial and ecological systems coexist. This finding has both ecological and policy significance: it underscores the urgent need to manage industrial emissions without compromising the ecosystem's carbon-regulating capacity, supporting Indonesia's Low Carbon Development Initiative (LCDI).

Temporally, the observed decline in NO_2 between 2019 and 2024 coincides with mangrove restoration initiatives, corroborating Murdiyarso et al. (2021), who identified vegetation regrowth as a key driver of local atmospheric improvement. The co-trend between NDVI increase and NO_2 reduction thus illustrates the vertical carbon coupling mechanism, where surface vegetation dynamics directly influence tropospheric gas concentrations, a relationship rarely examined at the regency scale. Previous global studies (Zhu et al., 2022; Fatoyinbo & Simard, 2013) largely addressed this coupling at continental or ecosystem levels, but this research provides empirical evidence at a finer resolution, offering new insights for subnational carbon monitoring.

Furthermore, this study demonstrates that spatial fragmentation of mangroves weakens carbon regulation efficiency. Fragmented patches in northern and central Musi Banyuasin show higher atmospheric gas concentrations, consistent with findings by Chen et al. (2021) and Thomas et al. (2017), who emphasized that fragmentation disrupts photosynthetic carbon uptake and microclimatic stability. This implies that spatial continuity, not just area extent, is a critical determinant of ecosystem functionality. Consequently, restoration strategies should prioritize corridor connectivity, echoing recommendations by Costanza et al. (2021) for maintaining landscape-scale ecological coherence in coastal management.

From a methodological perspective, this research expands the application of Google Earth Engine (GEE) by integrating Sentinel-2 and Sentinel-5P datasets to establish a quantitative link between vegetation indices and atmospheric gases. While prior studies have separately utilized these sensors for vegetation (Bunting et al., 2018) or pollution analysis (Veefkind et al., 2012), few have combined them in a unified spatial framework. This integration represents a technical innovation that enhances monitoring precision and replicability, particularly valuable for developing nations where ground-based data are limited.

Overall, the study advances the state of the art in blue carbon spatial analysis by situating Musi Banyuasin within the global discourse on coastal carbon resilience. The findings emphasize that effective climate policy must account for geographical structure and landscape connectivity in regulating vertical carbon fluxes. The inverse relationship between mangrove density and atmospheric gas concentration documented here provides a robust scientific basis for integrating ecosystem health indicators into Indonesia's Nationally Determined Contributions (NDCs) and spatial planning policies.

In conclusion, the geographical and statistical significance of the results demonstrates that mangrove ecosystems in Musi Banyuasin act as both carbon reservoirs and atmospheric stabilizers, and their preservation is essential not only for local biodiversity but also for regional climate mitigation. The strong empirical correlations derived from this study fill a critical data gap at the subnational scale, offering an evidence-based pathway toward climate-resilient and economically sustainable coastal governance.

4. Conclusions

This study establishes a scientific synthesis showing that the spatial configuration and connectivity of mangrove ecosystems fundamentally influence their capacity to regulate atmospheric gases and sustain coastal climate stability. The integration of multispectral vegetation indices with atmospheric gas data offers a novel spatial pathway to understand how horizontal ecological patterns drive vertical carbon exchanges. This approach reframes blue carbon research from static carbon estimation toward a dynamic, spatially informed model that links ecosystem structure, function, and atmospheric feedbacks.

The originality of this work lies in its development of an integrative, satellite-based framework that simultaneously quantifies vegetation health and atmospheric gas composition at a regional scale. This methodological innovation contributes to advancing spatial ecology and remote sensing applications for climate science, particularly in data-limited tropical regions. Conceptually, it strengthens the understanding of ecological connectivity as a key determinant of carbon regulation, while empirically demonstrating how mangrove landscape integrity supports both environmental and economic resilience.

In the broader context of sustainability and environmental policy, the study provides an evidence-based foundation for incorporating spatial ecosystem indicators into low-carbon development and coastal management strategies. By aligning ecological connectivity with climate governance, it advances the journal's mission to promote interdisciplinary knowledge that bridges spatial science, climate resilience, and sustainable development.

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Author Contribution

The author contributed to conceptualization, methodology, software, validation, formal analysis, investigation, resources, data curation, writing – original draft preparation, writing – review & editing, visualization, supervision, and project administration.

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Not available.

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Not available.

Data Availability Statement

All datasets analyzed in this study are publicly accessible. Sentinel-2 and Sentinel-5P datasets were obtained from the Copernicus Open Access Hub via Google Earth Engine (GEE) platform. Mangrove distribution data were derived from Global Mangrove Watch (UNEP-WCMC, 2020), and administrative boundaries were accessed from GADM (Global Administrative Database). The processed data and analytical workflow can be made available from the author upon reasonable request.

Conflicts of Interest

The author declare no conflict of interest.

Declaration of Generative AI Use

During the preparation of this work, the author used Claude to assist in improving academic tone, structure, and clarity of the manuscript, particularly for linguistic refinement. After using this tool, the author carefully reviewed, revised, and validated all content to ensure accuracy, originality, and full responsibility for the final published version.

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