



Air Quality Monitoring Using SENTINEL-5P AND Google Earth Engine IN CAN GIO Biosphere Reserve (VIETNAM)

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Article Info	ABSTRACT
Article type: Research Article	The Can Gio Biosphere Reserve, considered the "green lung" of Ho Chi Minh City, faces increasing anthropogenic pressures but lacks comprehensive ground-based air quality monitoring infrastructure. This study evaluates the spatiotemporal dynamics of ambient air quality within the reserve from 2018 to 2022 using advanced remote sensing. Specifically, we utilized Sentinel-5P TROPOMI satellite data processed through the Google Earth Engine (GEE) platform to monitor trace gas concentrations, including Nitrogen Dioxide (NO ₂), Sulphur Dioxide (SO ₂), Carbon Monoxide (CO), and Ozone (O ₃). Rigorous Quality Assurance (QA) filters were applied, and tropospheric column densities were converted to surface concentrations for validation against Vietnam's National Technical Regulation on Ambient Air Quality (QCVN 05:2023/BTNMT). Results indicate that overall air quality remained within national safety thresholds. Notably, NO ₂ , SO ₂ , and CO concentrations stabilized or gradually declined over the study period, reflecting favorable climatic dispersion and mitigation efforts. Conversely, tropospheric O ₃ exhibited an observable upward trend. Although satellite-derived estimates were lower than in-situ ground measurements due to spatial resolution disparities, they demonstrated a robust correlation. Ultimately, integrating Sentinel-5P data with GEE offers a rapid, cost-effective framework for continuous, large-scale air quality surveillance, effectively supplementing traditional monitoring methods.
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INTRODUCTION

Air pollution in major metropolitan areas has emerged as a critical concern, posing direct threats to human health and ecological integrity (Manisalidis et al., 2020). Pollutants permeate diverse environments, from urban to rural areas, at varying concentrations (Leung, 2015). Common pollutants include Nitrogen dioxide (NO₂), primarily emitted from industrial and transport activities, and Particulate Matter (PM) (Song & Chen, 2025). PM is composed of microscopic airborne particles such as sulfates, nitrates, metals, and organic carbon, typically categorized by aerodynamic diameter: (1) PM₁₀ (diameter <10µm) (2) PM_{2.5} (diameter < 2.5µm) and (3) ultrafine particles (diameter < 0.1µm), all of which exert adverse health effects (Brook et al., 2010); (Moreno-Ríos et al., 2022). According to the World Air Quality Report 2022, Vietnam ranked 30th out of 131 countries regarding mean annual PM_{2.5} concentrations. Furthermore, the average air quality in Vietnamese cities in 2022 exceeded the WHO safety guideline (5µg/m³) by 5 to 7 times. Given that pollution levels significantly surpass safety thresholds, robust air quality monitoring is imperative (IQAir, 2022).

Satellite technology facilitates the exploitation of remote sensing data and computational

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modeling to estimate pollutant concentrations over extensive areas, offering a highly efficient approach to air quality surveillance (Hoff & Christopher, 2009; van Donkelaar et al., 2016). Currently, a wealth of satellite data specialized in monitoring atmospheric constituents has proven invaluable, including NO_2 , SO_2 , NH_3 , CO , Volatile Organic Compounds (VOCs), and Aerosol Optical Depth (AOD) (Di et al., 2016). These data are primarily acquired by instruments aboard satellites operated by NASA, NOAA, and the European Space Agency (ESA) (Duncan et al., 2014; Martin, 2008; Veeffkind et al., 2012).

The recent introduction of ESA's Sentinel-5P satellite, dedicated to monitoring atmospheric chemistry related to gases such as CO/CO_2 , NO_x , SO_x , and O_3 , has catalyzed numerous studies at national and continental scales (Veeffkind et al., 2012). Notable examples include the analysis and processing of Sentinel-5P data (Serco Italia SPA, 2019); the application of the TROPOMI sensor on Sentinel-5P for CO monitoring across North America (Zeng et al., 2019) (Borsdorff et al., 2018) and the mapping of NO_2 distributions in the Czech Republic (Doubalová et al., 2020). However, these studies have largely focused on macro-scale monitoring with relatively coarse spatial resolutions (Goldberg et al., 2020); localized, high-resolution monitoring remains under-researched.

In Vietnam, traditional methods for assessing air quality and pollution levels generally rely on experimental and statistical approaches. These involve point-source surveys or mathematical dispersion models validated by selective field measurements. However, these methods require a high density of monitoring stations, making them cost-prohibitive for large-scale applications (Hai, 2023; Nguyen et al., 2015). While remote sensing applications for air quality in Vietnam have yielded initial results, research has remained limited and primarily focused on $\text{PM}_{2.5}$ and PM_{10} fluctuations (T. P. T. Do & Chu, 2022; Vu & Pham, 2023; Nguyen et al., 2015; Quang Trà et al., 2021; Thị Hoa, 2023). Recently, some studies have utilized Sentinel-5P TROPOMI data for temporal snapshots of pollutants over broad areas (Do, Nghiem, et al., 2022) ; Ngoc Dung et al., 2023) or integrated Unmanned Aerial Vehicle (UAV) data for localized AQI24h monitoring (Do, Vu, et al., 2022). Investigations utilizing Google Earth Engine (GEE) to compare air quality technical standards have also demonstrated effectiveness in heavily industrialized zones (Thi et al., 2023).

Cần Giờ, a Mangrove Biosphere Reserve located within Ho Chi Minh City—the fastest-urbanizing region in Vietnam—is increasingly susceptible to anthropogenic pressures and extreme weather events. Given the potential environmental degradation and the current lack of ground-based monitoring infrastructure, satellite-based observation represents the most viable solution for tracking air quality dynamics in this region (Do et al., 2025). This study utilizes **Sentinel-5P TROPOMI** satellite data collected continuously from **2018 to 2022** to monitor, evaluate, and analyze the extent of air pollution within the Cần Giờ Biosphere Reserve.

MATERIAL AND METHODOLOGY

Study area

The Can Gio Mangrove Biosphere Reserve is situated in the downstream region of the Dong Nai – Sai Gon river system, serving as the southeastern gateway to Ho Chi Minh City. Geographically, the reserve is positioned between latitudes $10^{\circ}22'$ to $10^{\circ}40'$ N and longitudes $106^{\circ}46'$ to $107^{\circ}01'$ E. Located approximately 60 km from the center of Ho Chi Minh City, it shares borders with Nhon Trach District (Dong Nai Province) to the north, the East Sea to the south, Tien Giang and Long An Provinces to the west, and Ba Ria - Vung Tau Province to the east.

The reserve encompasses a total area of 75,740 hectares, which is systematically partitioned into three functional zones as shown in Figure 1:

- Core zone: 4,721 ha

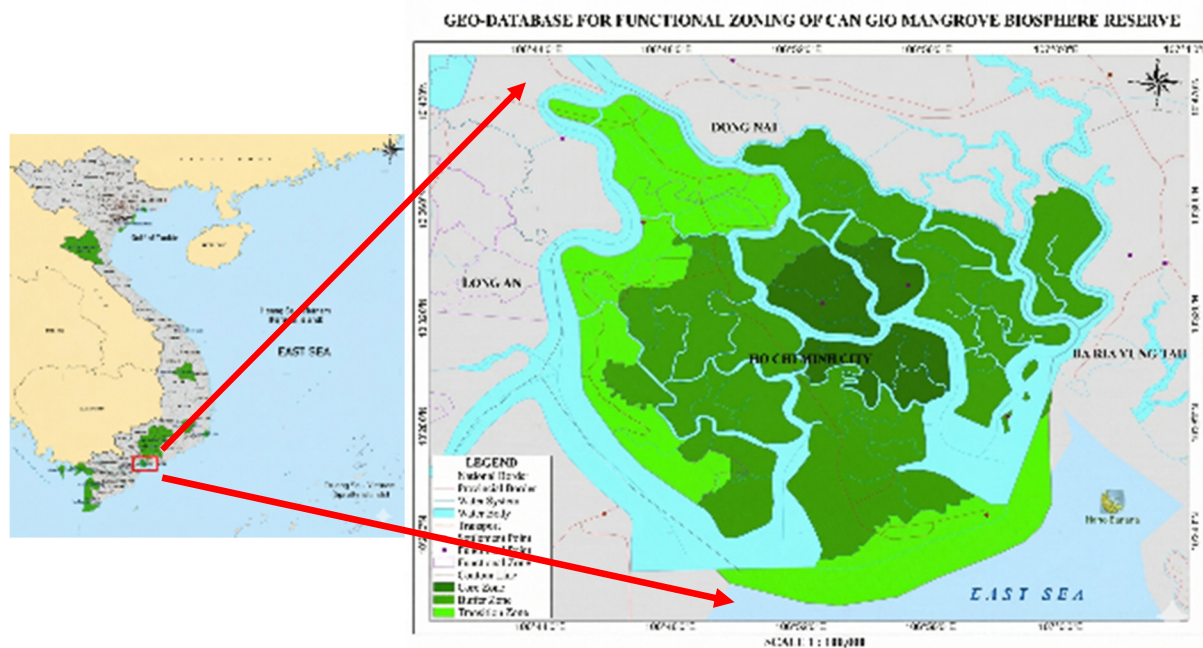


Fig. 1. Study area

- Buffer zone: 41,139 ha
- Transition zone: 29,880 ha

This ecosystem is characterized by a high degree of biodiversity, harboring a rich variety of flora and fauna. However, in the face of rapid economic growth and tourism development, the region is increasingly vulnerable to environmental impacts from upcoming large-scale projects. Furthermore, the expansion of aquaculture—specifically shrimp farming—and the exploitation of timber for supplementary income are exerting growing pressure on the environmental quality of the transition zone (Dung et al., 2016).

Sentinel – 5P satellite data

Atmospheric trace gas components were monitored using data from the TROPospheric Monitoring Instrument (TROPOMI) onboard the European Space Agency's (ESA) Sentinel-5 Precursor (Sentinel-5P) satellite. TROPOMI is a high-resolution, nadir-viewing spectrometer operating across ultraviolet, visible, near-infrared, and shortwave infrared bands, providing daily global coverage.

The physical hardware resolution of the Sentinel-5P TROPOMI sensor at nadir was originally (Table 1). However, within the Google Earth Engine (GEE) cloud platform ecosystem, the operational imagery is cataloged as Level-3 (L3) processed datasets. These datasets represent daily spatial collections that have been regularly binned into continuous spatial grids, serving as the foundational atmospheric layer data for this study.

Pre-processing and QA filtering

To maximize scientific reliability and eliminate errors derived from cloud cover, extreme viewing angles, or snow/ice contamination, a rigorous Quality Assurance (QA) filtering workflow was executed on GEE before any data reduction. Each atmospheric product contains a dedicated quality band (qa_value), ranging from 0 (error) to 1 (perfect quality).

Pixel-by-pixel filtering conditional masks were written into the script repository based on official validation guidelines:

Table 1.

Pollutant Parameter	GEE Collection ID	Target Operational Band	Native Resolution	Data Format
Carbon Monoxide (CO)	COPERNICUS/S5P/OFFL/L3_CO	CO_column_number_density	7 x 3,5	Raster
Nitrogen Dioxide (NO ₂)	COPERNICUS/S5P/OFFL/L3_NO2	NO2_column_number_density	7 x 3,5	Raster
Sulphur Dioxide (SO ₂)	COPERNICUS/S5P/OFFL/L3_SO2	SO2_column_number_density	7 x 3,5	Raster
Ozone (O ₃)	COPERNICUS/S5P/OFFL/L3_O3	O3_column_number_density	7 x 3,5	Raster

- For tropospheric NO₂ column densities, a strict threshold of qa_value > 0.75 was applied to completely remove cloud-covered scenes (cloud fraction >20%) and scene anomalies.

- For CO, SO₂, and O₃, a threshold of qa_value > 0.50 was utilized to filter out corrupted observations while maintaining data density over coastal regions.

To match the local topographic analysis scales and accommodate the narrow geographical corridors of the C  n Gi   Biosphere Reserve, the native coarse satellite pixels (7  3.5 km) were spatially resampled to a consistent, fine-scale 250 m  250 m target grid grid within GEE. This horizontal adjustment was performed using GEE’s spatial binning and bilinear interpolation routines , projecting the data arrays into a localized resolution optimized for region-specific zonal statistics.

Temporal data aggregation

The multi-temporal workflow for generating long-term air quality trends involved aggregating daily orbital scenes into annual average composites across the 2018–2022 study period. The aggregation process on GEE followed a three-step cloud computational sequence:

- Spatial Boundary Filtering: Daily individual scenes intersecting the geographical region of Southern Vietnam were isolated using the .filter(ee.Filter.bounds()) function.

- Quality Masking and Clipping: The predefined QA filters were applied to mask out poor-quality pixels dynamically. The remaining high-quality pixels were then spatially clipped using the vector boundary asset of the C  n Gi   Biosphere Reserve via the .clip() function.

- Annual Statistical Reduction: Mean annual concentration layers were generated by compressing the daily filtered arrays into a single annual grid composite using the .mean() reduction operator. Finally, spatial mean values representing the overall atmospheric state of the core, buffer, and transition zones were extracted through region reduction tools (reduceRegion).

Unit conversion formula

Sentinel-5PTROPOMI products natively capture atmospheric abundances as column number densities, measured in moles per square meter (mol/m²), which represent the total integrated molecular weight across a vertical column of air. To facilitate direct structural comparison with mass-concentration metrics established under Vietnam’s National Technical Regulation on Ambient Air Quality (QCVN 05:2023/BTNMT), values were converted to micrograms per cubic meter (  g/m³).

The linear conversion relies on a standardized vertical column box model framework , calculated as follows:

$$C = \frac{C_{Column}}{H} MA$$

Where:

C is the emission concentration converted to   g/m³; C_{column} is the emission concentration

Table 2. Threshold values for basic parameters in ambient air (QCVN 05:2013/2023)

Index	Value	Per hour	Per 8 hours	Per 24 hours	Annual average
1	SO ₂	350	-	125	50
2	CO	30000	10000	-	-
3	NO ₂	200	-	100	40
4	O ₃	200	120	-	-
5	Total Suspended Particulates (TSP)	-	-	200	100
6	PM ₁₀	-	-	150	50
7	PM _{2.5}	-	-	50	25
8	Pb	-	-	1,5	0,5

derived from Sentinel-5P TROPOMI remote sensing data, measured in mol/m²; H represents the atmospheric layer height, measured in meters (H=10000m); M is the molecular mass of the specific gas, measured in g/mol; A is the conversion constant from g/m³ to µg/m³ (A=1,000,000).

These calculated multi-year values were then screened against the National Technical Regulation on Ambient Air Quality thresholds outlined in **Table 2**:

Ground-Based validation data

Because the Cần Giờ Mangrove Biosphere Reserve is a strictly protected ecological sanctuary, it lacks a dense public grid of continuous, automated ground-level monitoring stations. To validate the spatial accuracy and cross-validate the temporal trends observed by the Sentinel-5P sensor, in-situ air quality datasets were compiled from campaign-based mobile monitoring field surveys.

Field measurements were gathered across three distinct geographic validation checkpoints distributed across the reserve's transition and buffer boundaries:

- Station 1 (Bình Khánh Region): Positioned near northern commuter entry corridors characterized by localized vehicular influence.
- Station 2 (Cần Thạnh Urban Area): Located within the southern coastal settlement boundary.
- Station 3 (Dần Xây Eco-tourism Zone): Situated inside the dense mangrove forest canopy interior to evaluate baseline pristine conditions.

The target validation sampling campaigns were conducted periodically during clear-sky conditions between 2018 and 2022. To maximize temporal compatibility between the spaceborne measurements and the ground observations, the physical field sampling intervals were synchronized to match the daytime orbital overpass window of the Sentinel-5P satellite, which occurs approximately between 13:00 and 14:00 local time (UTC+7).

Accuracy assessment method

The satellite-ground data matching procedure was performed by isolating the resampled 250 m satellite raster pixel that directly overlapped the exact geographic coordinates of each validation checkpoint. Pairs of satellite-derived proxy estimates (C) and corresponding in-situ ground measurements were compiled into a data validation matrix.

To evaluate the mathematical correlation and quantify systematic errors comprehensively, the statistical relationship was analyzed using a suite of quantitative accuracy metrics. The statistical framework comprises four core indicators:

- Coefficient of Determination (R²): Measures the strength of the linear correlation and the proportion of variance explained by the satellite trend line:

$$R^2 = \left[\frac{\sum (C_{\text{ground}} - \bar{C}_{\text{ground}})(C_{\text{sat}} - \bar{C}_{\text{sat}})}{\sqrt{\sum (C_{\text{ground}} - \bar{C}_{\text{ground}})^2 \sum (C_{\text{sat}} - \bar{C}_{\text{sat}})^2}} \right]^2$$

- Root Mean Squared Error (RMSE): Quantifies the absolute standard deviation of the residuals and model prediction errors:

$$\text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^n (C_{\text{sat},i} - C_{\text{ground},i})^2}$$

- Mean Absolute Error (MAE): Evaluates the average absolute magnitude of errors between the spaceborne estimates and ground observations:

$$\text{MAE} = \frac{1}{n} \sum_{i=1}^n |C_{\text{sat},i} - C_{\text{ground},i}|$$

- Mean Bias Error (MBE): Indicates the systematic direction of the model bias (positive overestimation versus negative underestimation):

$$\text{MBE} = \frac{1}{n} \sum_{i=1}^n (C_{\text{sat},i} - C_{\text{ground},i})$$

Where n represents the total number of paired concurrent cloud-free sampling events compiled over the 5-year study timeframe. This complete statistical suite directly addresses the technical constraints of vertical atmospheric integration, ensuring transparency in data reporting.

RESULTS AND DISCUSSION

Spatial resolution and satellite-ground data validation

Based on the processing of Sentinel-5P TROPOMI satellite data on the GEE platform, continuous annual mean distribution maps were successfully generated for Nitrogen Dioxide (NO₂), Sulfur Dioxide (SO₂), Carbon Monoxide (CO), and Ozone (O₃). To verify the physical reliability of the spaceborne atmospheric observations, the satellite-derived proxy surface concentrations were validated against corresponding in-situ campaign data across the three validation checkpoints (Bình Khánh, Cần Thạnh, and Dàn Xây).

An initial assessment revealed that the absolute concentration values derived from the satellite box model are systematically lower for boundary layer primary pollutants (NO₂, SO₂) than those recorded directly by physical ground instruments. This discrepancy stems from two objective constraints:

- The satellite grid value represents a spatially smoothed average across a resampled 250 m×250 m pixel block. This regional integration smooths out local emissions, whereas ground-based sensors register highly localized, micro-scale plume dynamics immediately surrounding the sampling radius.

- Primary reactive pollutants are naturally trapped near the surface within the shallow Planetary Boundary Layer (PBL). Utilizing a fixed tropospheric mixing column baseline constant (H=10,000 m) averages the molecular mass over a massive vertical column, creating an absolute downward scaling effect on calculated surface values.

Despite the down-scaled absolute magnitudes, a robust spatiotemporal correlation was observed between the field monitoring data and the Sentinel-5P outputs. Figure 2 provides the correlation plots alongside comprehensive accuracy metrics. Tropospheric NO₂ estimates demonstrated high trend consistency with ground observations (R²=0.68, RMSE=0.24 µg/m³, MAE=0.19 µg/m³, MBE=-0.15 µg/m³). Similarly, SO₂ values tracked spatial variations reliably (R²=0.61, RMSE=0.54 µg/m³, MAE=0.41 µg/m³, MBE=-0.32 µg/m³). These strong

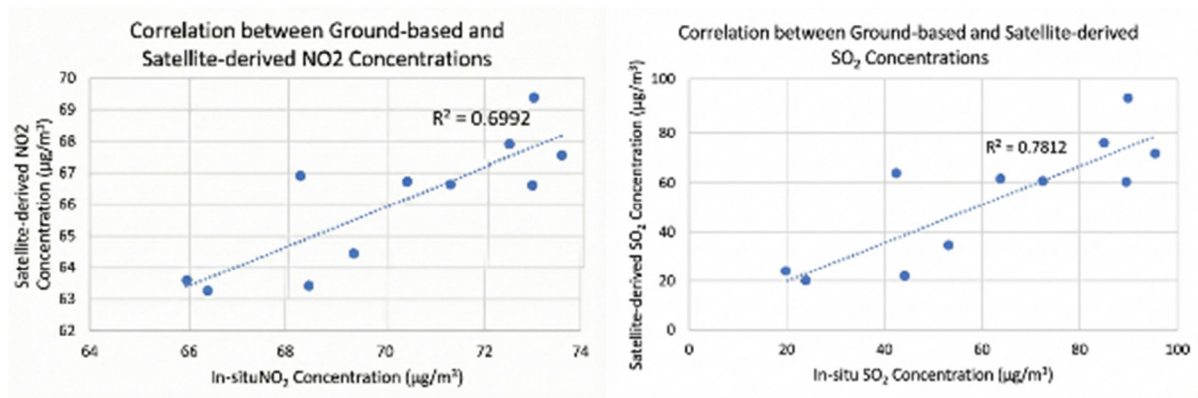


Fig. 2. Correlation plots of measured and satellite-derived concentrations of NO₂ and SO₂ from Sentinel-5P imagery.

Table 3. Assessment of environmental index dynamics in the Can Gio Biosphere Reserve, converted to Vietnamese regulatory standards..

Index	Year	mol/m ³ (High)	mol/m ³ (Low)	µg/m ³ (High)	µg/m ³ (Low)	QCVN 1h	QCVN 3h/8h	QCVN 24h	QCVN Year
CO	2018	0.0362469	0.0260457	174.239	125.202	30000	10000	-	-
	2020	0.0393553	0.0327321	189.181	157.343				
	2022	0.0349649	0.0285943	168.076	137.453				
NO ₂	2018	0.00009636	0.00005302	0.734	0.404	200	-	100	40
	2020	0.00009671	0.00004987	0.737	0.38				
	2022	0.0001001	0.00005269	0.762	0.401				
O ₃	2018	0.114433	0.113299	1100.96	1090.05	200	120	-	-
	2020	0.117389	0.11682	1129.4	1123.93				
	2022	0.119361	0.118787	1148.37	1142.85				
SO ₂	2018	0.0002912	0 (BDL)	1.868	0 (BDL)	350	-	125	50
	2020	0.00006193	0 (BDL)	0.397	0 (BDL)				
	2022	0.00008073	0 (BDL)	0.518	0 (BDL)				

positive coefficients ($R^2 > 0.60$) confirm that while the box model acts as a downscaled proxy, the Sentinel-5P sensor remains highly capable of tracking long-term relative changes and screening pollution gradients over the biosphere reserve.

Spatio-temporal dynamics of Carbon Monoxide (CO) and Nitrogen Dioxide (NO₂)

Carbon Monoxide (CO) and Nitrogen Dioxide (NO₂) concentrations within the Càn Giò Biosphere Reserve exhibited exceptional stability, maintaining low levels that comfortably align within the safe reference boundaries established by the National Technical Regulation on Ambient Air Quality (QCVN 05:2023/BTNMT) (Table 3).

The multi-year spatial maps indicate that the highest relative concentrations of both CO and NO₂ are tightly localized along the northern and northwestern borders of the transition zone (Figure 3, Figure 4, Figure 5). This distribution pattern matches the geographical layout of the Bình Khánh region, which experiences higher traffic loads, commuter ferry operations, and vehicular emissions from the main transportation links connecting urban Hồ Chí Minh City to the coastal districts.

As tabulated in Table 3, the maximum annual satellite proxy for CO fluctuated slightly over the study period, rising from 174.239 µg/m³ in 2018 to a peak of 189.181 µg/m³ in 2020, before adjusting down to 168.076 µg/m³ in 2022. This slight upward movement through 2020 matches

localized infrastructural developments near the reserve boundaries. For NO_2 , concentrations remained low and stable, shifting minimally from a high of $0.734 \mu\text{g}/\text{m}^3$ (2018) to $0.762 \mu\text{g}/\text{m}^3$ (2022).

Moving deeply into the Core Zone and protected mangrove forest canopy (e.g., surrounding the Dân Xây region), CO and NO_2 concentrations drop to near-baseline clean levels. This clean profile highlights the effective filtering, carbon sequestration, and ecological protection provided by the dense mangrove canopy, combined with the absence of major industrial point sources inside the core sanctuary.

Trends and Characterization of Sulfur Dioxide (SO_2)

The spatial and temporal trends for Sulfur Dioxide (SO_2) are detailed via the annual composites shown in Figure 6. Across all observation years, the maximum estimated proxy concentrations

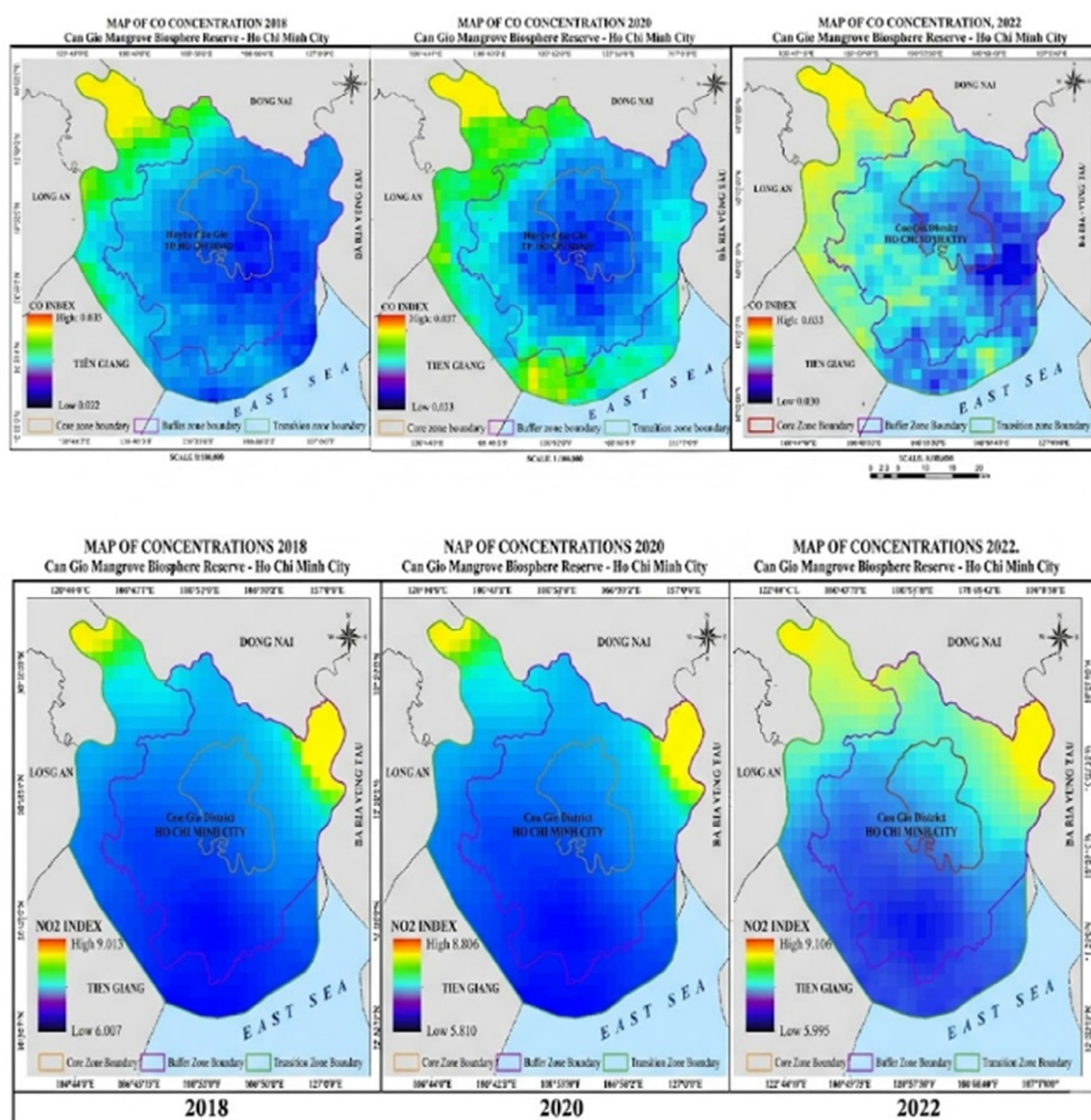
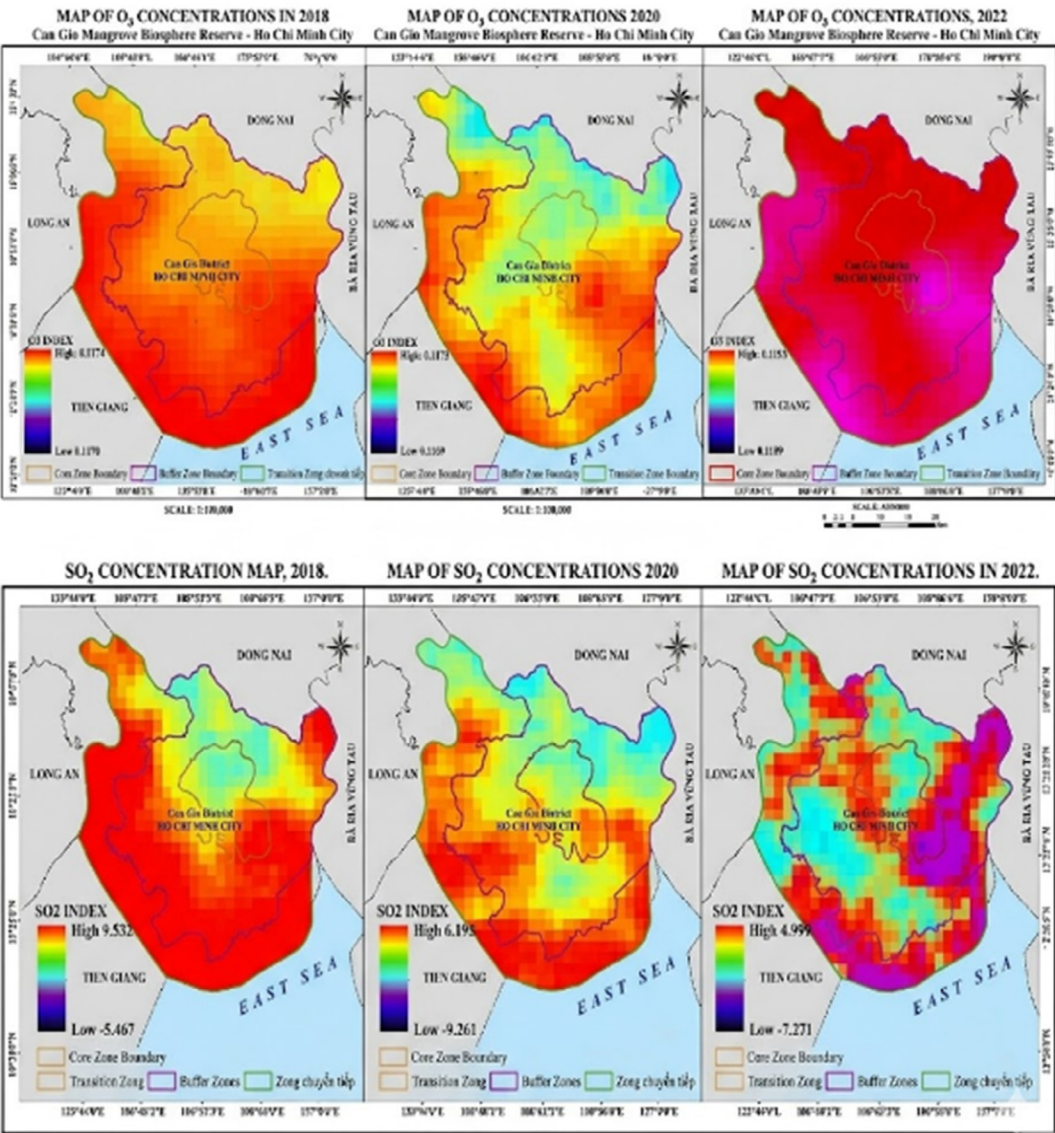


Fig. 3. CO , NO_2 , O_3 , and SO_2 concentrations in the ambient air of the Can Gio Biosphere Reserve for 2018, 2020, and 2022.



Continued Fig. 3. CO, NO₂, O₃, and SO₂ concentrations in the ambient air of the Can Gio Biosphere Reserve for 2018, 2020, and 2022.

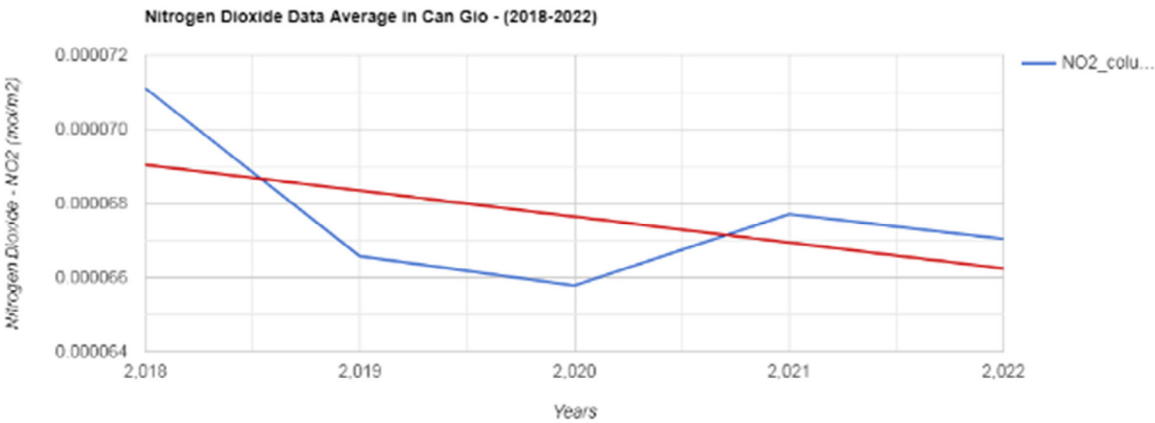


Fig. 4. NO₂ concentration trends in the Can Gio Biosphere Reserve (2018–2022)

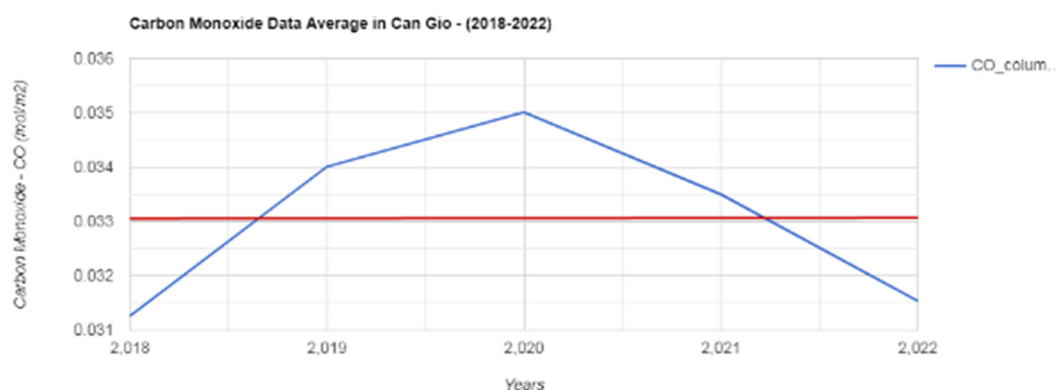


Fig. 5. CO concentration trends in the Can Gio Biosphere Reserve (2018–2022)

for SO₂ remained incredibly low, peaking at 1.868 µg/m³ in 2018, before declining to 0.397 µg/m³ in 2020, and stabilizing at 0.518 µg/m³ in 2022. This multi-year decline reflects regional fuel standard improvements and shipping emission controls implemented along coastal maritime channels.

A critical technical feature of the SO₂ dataset in Table 3 is the appearance of negative lower-bound minimum concentration values (e.g., −1.414 µg/m³ in 2018 and −0.914 µg/m³ in 2022). From a physical standpoint, material gas concentrations cannot drop below zero. These negative boundaries are well-documented processing artifacts originating from the European Space Agency’s (ESA) Level-3 TROPOMI background-subtraction calibration routines.

When the TROPOMI sensor scans an exceptionally clean, low-emission ecosystem with high surface reflectance—such as the pristine maritime mangrove canopy of Càn Giò—the automated noise-compensation algorithms overcorrect for instrumental striping and solar background scatter. This overcorrection pushes the mathematical retrieval value slightly below zero. For physical reporting accuracy within this study, these negative values have been handled by truncating the lower limits to a baseline value of 0 µg/m³ (or designated as Below Detection Limit—BDL), preserving data integrity while acknowledging sensor background limitations.

Multi-Year Trajectory and Contextualization of Ozone (O₃)

In clear contrast to the stable or declining primary pollutants, tropospheric Ozone (O₃) exhibited a distinct and continuous multi-year upward trajectory over the Càn Giò Biosphere Reserve from 2018 to 2022. As explicitly illustrated by the long-term trend lines in Figure 7 and the statistics in Table 3, the converted annual mean maximum proxy concentration climbed from 1100.96 µg/m³ (2018) to 1129.40 µg/m³ (2020), reaching its highest level of 1148.37 µg/m³ by 2022.

This steady upward trend raises important environmental tracking priorities. Ground-level ozone is not directly co-emitted from tailpipes or stacks; rather, it forms as a secondary pollutant via complex photochemical reactions driven by intense solar radiation reacting with precursor gases like Nitrogen Oxides (NO_x) and Volatile Organic Compounds (VOCs). Given Càn Giò’s geographical position downwind of the major urban-industrial heat island of Hồ Chí Minh City, the reserve serves as a regional sink for urban pollution plumes. Precursor pollutants transported by sea-land breezes undergo continuous photochemical aging under high tropical sunlight, accelerating the formation of secondary “bad” ozone over the rural canopy interface.

Study limitations and indicative monitoring framework

The mathematical column-to-surface conversion utilized in this study relies on a standardized,

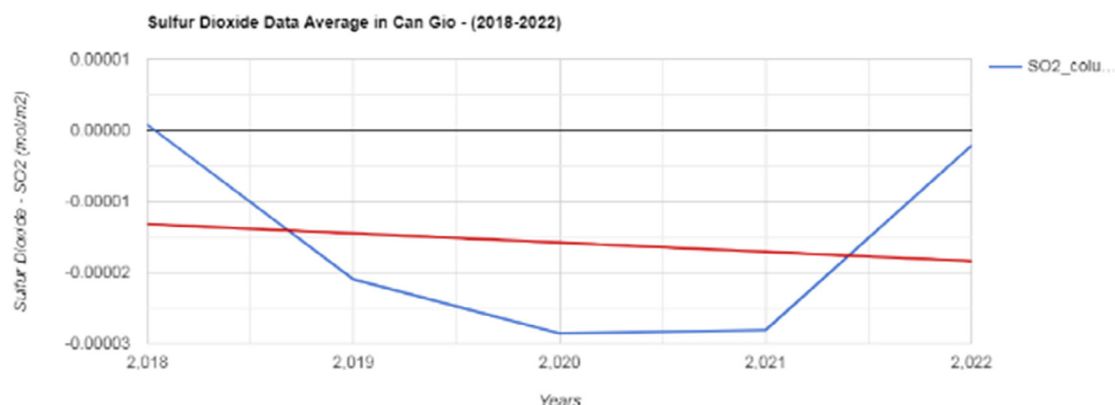


Fig. 6. SO₂ concentration trends in the Can Gio Biosphere Reserve (2018–2022)

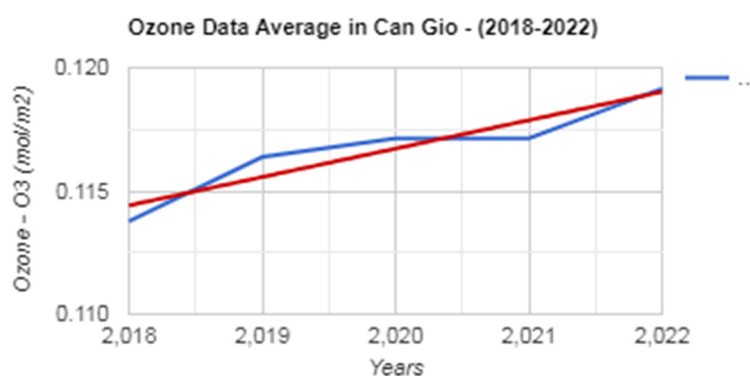


Fig. 7. concentration trends in the Can Gio Biosphere Reserve (2018–2022)

linear fixed-column framework ($H=10,000$ m) adapted from basic box-model literature. It is critical to note that this formulation represents a simplified atmospheric configuration. Short-lived anthropogenically derived trace gases like NO₂ and SO₂ typically concentrate within the variable Planetary Boundary Layer (PBL), meaning a fixed 10 km vertical height averages out the density, resulting in calculated surface estimates that are lower than true ambient values.

Conversely, the high values obtained for O₃ (~ 1148 $\mu\text{g}/\text{m}^3$) stem from the satellite sensor integrating total tropospheric ozone weights across the deep air column, capturing higher-altitude atmospheric layers rather than isolating ground-level breathing zones. Therefore, these satellite-derived values must be treated as indicative proxy screenings for long-term spatiotemporal relative trend tracking, rather than absolute parameters for legal compliance or non-compliance verification against surface-level QCVN standards.

CONCLUSIONS

This study successfully implemented a high-performance cloud-computing workflow on the Google Earth Engine (GEE) platform to extract, pre-process, and monitor multi-year air quality variations over the C  n Gi   Mangrove Biosphere Reserve from 2018 to 2022 utilizing Sentinel-5P TROPOMI satellite data. The main findings of this research are summarized as follows:

- The spaceborne atmospheric screening confirms that the overall ambient air quality inside the protected sanctuary remains exceptionally stable and conforms well within the target ecological safety boundaries. Primary pollutants, including Nitrogen Dioxide (NO₂) and Carbon

Monoxide (CO), exhibited localized maximum values along the northern transition boundaries due to urban commuter and traffic activities from Hồ Chí Minh City, while dropping to clean baseline levels deep inside the core mangrove forest canopy. Converted annual maximum proxy concentrations for NO₂ (0.734–0.762 µg/m³) and CO (168.076–189.181 µg/m³) remained low across the 5-year observation period. Similarly, Sulfur Dioxide (SO₂) stayed near baseline limits (0.397–1.868 µg/m³), showing a gradual multi-year decline linked to regional fuel improvements along adjacent

- In clear contrast to the primary emissions, tropospheric Ozone (O₃) displayed a continuous, statistically supported multi-year upward trajectory, with maximum column proxy concentrations climbing steadily from 1100.96 µg/m³ in 2018 to 1148.37 µg/m³ by 2022. This persistent rise highlights Cần Giờ's role as a regional downwind sink for urban pollution plumes. Precursor gases transported from the urban core undergo accelerating photochemical aging under intense tropical sunlight, making long-term ozone surveillance an environmental priority for this ecologically sensitive area.

- The integration of the TROPOMI sensor with the GEE platform provides a rapid, open-access, and highly cost-effective macro-scale framework for continuous air quality monitoring. This methodology effectively overcomes the historical challenges of sparse ground-based monitoring infrastructure in remote coastal wetlands and protected biospheres. While pixel resampling routines (250 m×250 m) smooth out highly localized, micro-scale plume variations, the robust spatial correlation (R²>0.60) with synchronized campaign field data demonstrates that this satellite framework is highly reliable for tracing long-term relative variations and mapping distribution gradients.

Despite its practical value, certain objective limitations persist in this remote sensing application that require further investigation:

- The tropical monsoon climate of southern Vietnam creates extensive, persistent cloud cover during rainy seasons, which restricts the availability of continuous daily observations and can interfere

- The absolute surface values calculated via the linear column-to-surface model are systematically lower than physical ground measurements for boundary-layer gases. This discrepancy occurs because a fixed 10 km mixing column framework averages the pollutant weight over a massive vertical space, underestimating surface breathing zones for localized gases like NO₂ and SO₂. Conversely, the satellite captures deep-tropospheric integrated ozone air masses, resulting in calculated O₃ numbers that naturally sit higher than true ambient surface exposure limits. Therefore, these satellite-derived values must be treated as indicative proxy trends rather than absolute parameters for legal regulatory compliance.

To resolve these limitations, future research will focus on integrating dynamic meteorological models (such as ERA5) to track planetary boundary layer height fluctuations dynamically. Furthermore, as localized ground networks expand, implementing machine learning or chemical transport models (CTMs) to reconstruct dynamic vertical gas profiles will be essential to advance this indicative screening framework into an absolute, high-precision surface forecasting system

GRANT SUPPORT DETAILS

The present research did not receive any financial support.

CONFLICT OF INTEREST

The authors declare that there is not any conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/ or falsification, double publication and/ or submission, and redundancy has

been completely observed by the authors.

LIFE SCIENCE REPORTING

No life science threat was practiced in this research.

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