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Air Quality Assessment in a Protected Natural Area: A Case Study of Banco Forest, Abidjan (Côte d'Ivoire)

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Abstract

Protected areas play a crucial role in biodiversity conservation, the provision of ecosystem services, and the mitigation of climate change impacts. Although theoretically shielded from anthropogenic activities, these areas are often perceived as reservoirs of clean air. However, recent studies have highlighted a growing level of atmospheric pollution even within these zones. This study aims to assess the air quality within Banco Forest, a national park located in an urban area of Abidjan, Côte d'Ivoire, to determine whether it still fulfills its function as an ecological buffer zone. The research was conducted between February and April 2021, using two air quality monitoring stations: one located near the Northern Highway, specifically at the Ivorian Office of Parks and Reserves (OIPR), and the other within Banco Forest, at the Forestry School of the park. Measurements indicated that the daily mean concentrations of fine particulates matter (PM2.5 and PM10), sulfur dioxide (SO_2), and nitrogen dioxide (NO_2) in Banco forest are comparable to those recorded near the heavily trafficked road, and often exceed both national air quality standards and the guidelines set by the World Health Organization (WHO). Nevertheless, the Air Quality Index (AQI) in Banco forest remains generally acceptable and is better than that observed in the traffic area between 9 p.m. and 8 a.m. These findings highlight the vulnerability of urban protected areas like Banco forest to air pollution and underscore the need for enhanced environmental monitoring and the integration of such spaces into public air quality management policies.

Keywords

Air Quality Assessment, Air Quality Index (AQI), Banco Forest, Côte d'Ivoire

1. Introduction

Protected areas are defined as geographical spaces that are designated, recognized, dedicated, and managed through legal or other effective means to ensure the long-term conservation of nature along with the associated ecosystem services and cultural values (Dudley 2008; Kholodov & Golokhvast, 2020). These areas are devoid of direct human activities and, as a result, are largely free from pollution. They offer critical ecosystem services that support human health and enhance resilience to climate change (Sharkey et al., 1991; Guenther, 2002; Nowak & Van Den Bosch, 2018). Natural reserves are essential for the conservation of biodiversity, the protection of ecosystems, the implementation of scientific research, and environmental education. They also offer opportunities for sustainable and eco-friendly tourism. These areas are generally considered to be free from anthropogenic disturbances and are expected to provide clean air and other critical ecosystem services. However, recent studies have reported increasing concentrations of atmospheric pollutants even within protected natural parks worldwide, raising serious concerns about their ability to maintain ecological integrity and ensure long-term environmental health (McMeeking et al., 2005). Since Côte d'Ivoire's independence in 1960, the issue of forest heritage conservation has been a central concern for public authorities (Sako et al., 2013). With the aim of more effectively conserving its forest heritage, the Ivorian government has facilitated the establishment of a comprehensive network of protected areas, encompassing nearly 10% of its territory (Dibi et al., 2008). Within its National Development Plan (PND 2021-2025), the Ivorian government has instituted some important measures to safeguard natural parks and reserves. Notably, the Banco forest plays an indispensable role in purifying the air of Abidjan. The Banco National Park, one of the last remnants of dense, evergreen humid forest, faces significant threats from rapid spatial expansion driven by population growth and the intensification of industrial and commercial activities in the district of Abidjan (Sako et al., 2013). The Banco Park has endured the consequences of agricultural and later urban development on the outskirts of its forest, as well as human settlements within the park itself (including the establishment of a forestry school in 1937 and the installation of mechanics' workshops in 1977, coinciding with the opening of the right-of-way for high-voltage power lines). The park was home, albeit rarely, to species such as the harlequin guenon, several monkey species (including the Hocheur, Petaurista, and Mone), around a dozen chimpanzees, and birds threatened by poaching and various forms of aggression (BRAO UICN, 2008). Among the various pressures confronting Banco National Park is air pollution, primarily attributable to its proximity to the Northern Highway and the industrial zone of Yopougon (one of the crowded and vast municipality of the district of Abidjan). In this context, the present study is conducted to assess the air quality over the natural reserve of Banco forest. The primary objective of this research is to evaluate the air quality within Banco forest. Specifically, the study focuses on analyzing temporal trends in atmospheric pollutant concentrations and determining the Air Quality Index (AQI) within the forest ecosystem. Section 2 of the paper describes the materials and methods. Then, Section 3 highlights the results and discussion. Finally, the main findings and the conclusion are given in Section 4.

2. Materials and Methods

2.1. Description of the Study Area

The present study was carried out within the District of Abidjan, specifically in the Banco forest, also called Banco National Park. The Park of Banco is located in the southern region of Côte d'Ivoire, along the Gulf of Guinea coastline. In Abidjan, hourly wind speed varies from 2.5 to 3.3 m/s and it blows from southwest direction. The minimum speed is reached in the morning at 6 a.m. and the maximum in the afternoon at 4 pm (Kone et al., 2024). Average daily temperatures show a range of 31˚C to 35˚C in Abidjan (Gnamien et al., 2021). In general, the average annual precipitation in the Abidjan district is about 2000 mm, with a transitional equatorial climate divided into four seasons in the annual cycle, the great dry season from December to April, the great rainy season from May to July, the little dry season from July to September, and the little rainy season from October to November (Konaté et al., 2016).

The park is distinguished by its characteristic fauna and flora representative of the tropical dense humid forest biome. Covering an area of 3438.34 hectares in the heart of Abidjan, the economic capital of Côte d'Ivoire, the park lies between latitudes 5˚21' and 5˚25' N and longitudes 4˚01' and 4˚05' W. It is limited as shown in **Figure 1** to the north by the municipality of Abobo, as defined by Decree No. 95-530 of 14th July 1995, which establishes the territorial boundaries between Abobo and Cocody; to the east and southeast by the municipality of Adjamé; to the south and southwest by the municipality of Attécoubé, in accordance with Decree No. 95-531 of 14th July 1995, which delineates the boundaries between Attécoubé and Yopougon; and to the west by the municipality of Yopougon. The adjacent neighborhoods including Anonkoua-Kouté (Abobo), Abobo-Sagbé (Abobo), SODECI (Adjamé), Agban-village (Attécoubé), Agban-Attié (Attécoubé), and Andokoi (Yopougon) are characterized by high population densities.

2.2. Location and Characteristics of the Different Sites of Data Collection

Data collection is conducted within Banco National Park at two primary sites: the entrance of the Ivorian Office of Parks and Reserves (OIPR), located near the

Northern Highway and characterized by heavy road traffic; and the Forestry School, located within the Banco forest distant from direct sources of air pollution. There was no spatial constraint for the study; however, it aimed to compare pollutants concentrations levels between the two monitoring sites.

The geographical coordinates of these sites as shown in Figure 2 were determined using a GARMIN-type GPS device. These coordinates are summarized in Table 1.

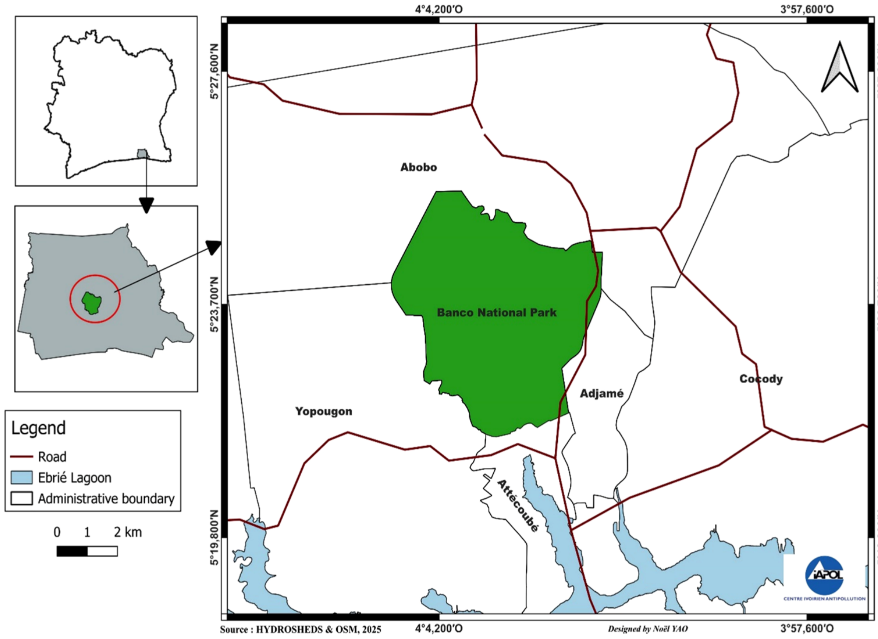

Figure 1. Location of the Banco National park.

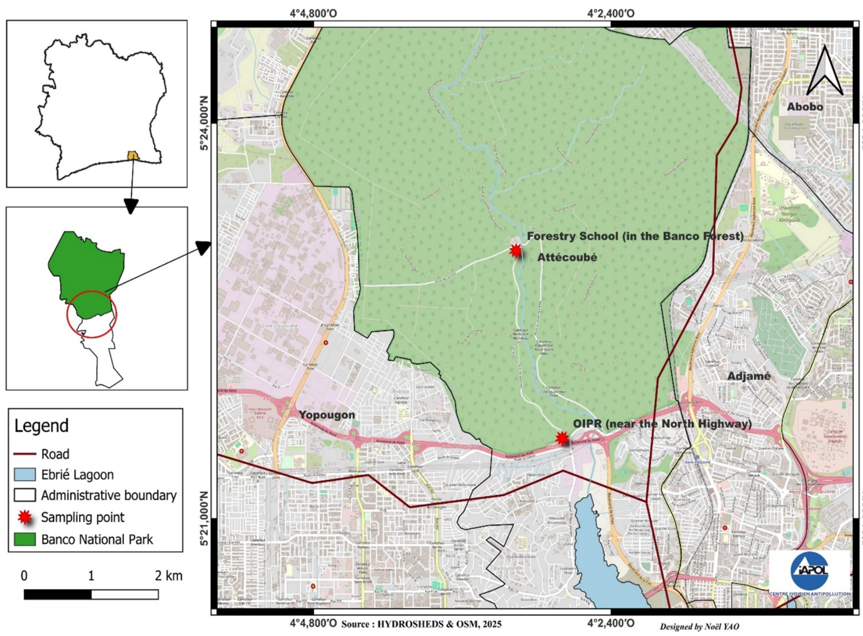

Figure 2. Location of the measurement sites.

Table 1. Geographical coordinates of the measurement sites.

Measurement points	Location	North Latitude	West Longitude
1	Entrance of the OIPR (near the North Highway)	5.36014	−4.04656
2	Forestry School (in the heart of Banco Forest)	5.38386	−4.05275

2.3. Description of the Data Collection Equipment

The data collection equipment used in this study consisted of two (2) mini-stations known as Cairnet positioned as shown in **Figure 3** which main components are illustrated in **Figure 4**. Cairnets are developed by the ENVEA Cairpol group, designed to establish a monitoring network for the continuous measurement of five (5) keys atmospheric pollutants (NO_2, CO, SO_2, PM10, PM2.5), with data collected at five-minute intervals. Cairnets sensors were co-located with reference analysers (cairsens), this makes data quality improved.

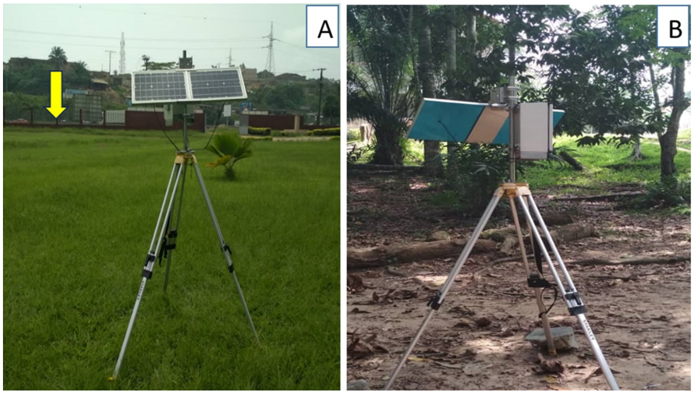

Figure 3. Location of the Cairnets at the measurement sites (A: OIPR near the highway indicated by the yellow arrow; B: Forestry School in the Banco forest).

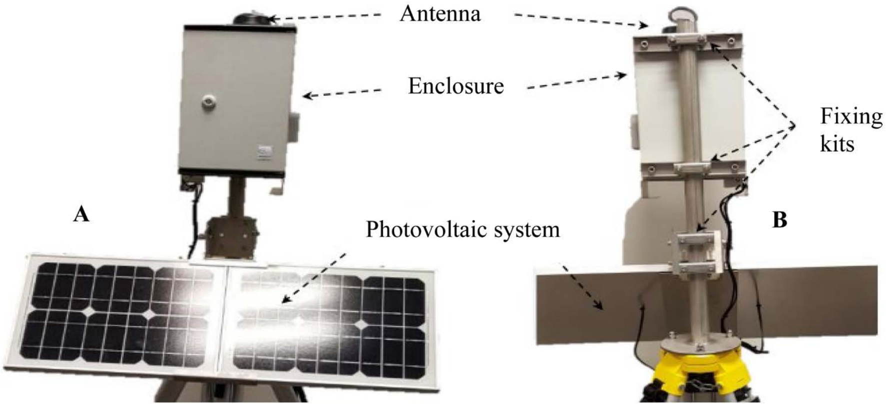

Figure 4. Description of the Cairnet, (A): front view, (B): rear view.

Each Cairnet unit is equipped with a solar panel to power a battery, a support structure, and a box as shown in **Figure 5** that contains electrochemical sensors (Cairsens) with a maximum operational lifespan of one (1) year. These sensors operate under specific environmental conditions, including a temperature range of −10 ˚C to 50 ˚C and relative humidity between 10% and 90%, enabling the continuous monitoring of pollutant concentrations as well as meteorological parameters such as temperature and relative humidity.

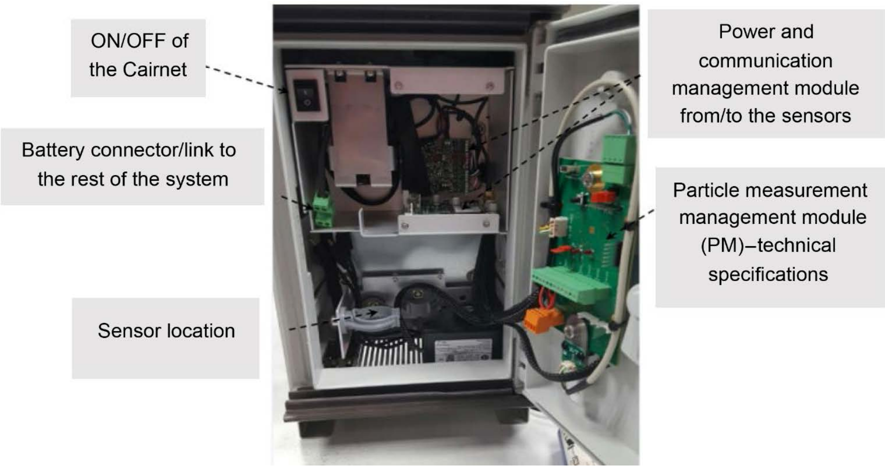

Figure 5. Presentation of the inside of the Cairnet box.

2.4. Operating Principle and Data Processing

The measured pollutants' concentrations by the sensors are transmitted to the File Transfer Protocol (FTP) server (Caircloud), which displays them at various levels. The access of the Caircloud server is established via an internet connection. Concentration data are obtained for selected time intervals (estimated about 1; 5 and 15 minutes, or sometime till hourly, or daily). The data are available for downloading in several formats, including XLS, CSV, PDF, SVG, JPEG, and PNG. This data collection process is illustrated in **Figure 6** (ENVEA, 2018).

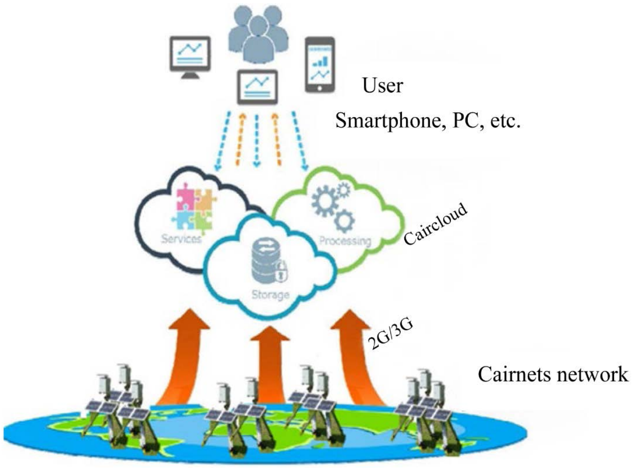

Figure 6. Data collection process.

Daily average concentrations were visualized using Microsoft Excel software over the study period, spanning the period from February 24th 2021, to April 15th 2021.

The measured concentrations were compared to the threshold values established by the national air quality decree (Decree no. 2017-125 of February 22nd 2017) and the standards set by the World Health Organization (WHO) (see **Table 2**). Statistical analyses including mean, standard deviation and coefficient of variation for hourly and daily concentrations were performed using GraphPad Prism software.

Table 2. Pollutants thresholds values from the air quality decree and world Health Organisation (WHO) standards (République de Côte d'Ivoire, 2017; WHO, 2021).

Pollutants	Time-weighted average	Threshold values (μg/m³)	
		Côte d'Ivoire	WHO
Nitrogen Dioxide (NO_2)	Daily	-	25
	Annual	40	10
Sulfur Dioxide (SO_2)	Daily	125	40
Carbon Monoxide (CO)	1 hour	-	35,000
	8 hours	10,000	10,000
PM2.5	Daily	-	15
	Annual	25	5
PM10	Daily	50	45
	Annual	40	15

2.5. Air Quality Index (AQI) Calculation

According to the United States Environmental Protection Agency (EPA), the Air Quality Index (AQI) is a parameter used to report daily air quality. This index indicates in which the air we breathe is clean or polluted. This index is also associated to the level of health concern, and the potential health effects.

Sub-index of a Pollutant

The sub-index (Ip) of a pollutant is calculated using the following formula:

$$(\text{Ipi}) = \frac{(\text{Pollutant's concentration})}{(\text{Threshold value})} * 100 \quad (1)$$

where **(Ipi)** is the index of a considered pollutant (for example i = O_3, PM2.5; PM10, CO, NO_2, SO_2).

Threshold value is the limit value of the pollutant, based on the national standard (if available) or the World Health Organization (WHO) guideline.

Air Quality Index (AQI)

The Air Quality Index (AQI) corresponds to the highest sub-index, as it represents the most harmful pollutant measured:

$$\text{AQI} = \max(I_{Pi}) \quad (2)$$

The threshold concentrations of pollutants used in this study are based on Decree No. 2017-125 on February 22nd, 2017, concerning air quality in the Republic of Côte d'Ivoire (see **Table 2**).

Hourly average concentrations, from 00:00 to 23:00, were used to calculate the daily AQI.

AQI values are divided into intervals of 50, which are numbered and color-coded to indicate the associated level of health concern and its interpretation. These ranges span from a standard healthy level of zero (0) to a hazardous level above 300, indicating the degree of health risk associated with the ambient air quality. These health risk levels are also associated with six (6) levels of air pollution severity (see **Table 3**):

Level 1 indicates good and healthy air quality. Air in this category is considered satisfactory and poses little or no health risk.

Level 2 is acceptable; however, there may be a moderate health concern for a very limited number of people, particularly those who are unusually sensitive to air pollution (e.g., individuals with asthma).

Level 3 is classified as unhealthy for sensitive groups. This level may not affect the general population, but individuals with pre-existing conditions such as respiratory or cardiovascular diseases, as well as vulnerable persons like children and the elderly who are at increased risk.

Level 4 is considered unhealthy; some members of the general public may experience adverse health effects, while sensitive groups may experience more serious health issues.

Level 5, marked with a purple colour code, is very unhealthy for the general population and will trigger a health alert, as the risk of adverse health effects is elevated and more severe for everyone.

Level 6 corresponds to a hazardous level of air pollution. This level will also trigger a health warning, indicating a significantly increased and severe risk to public health across the entire population.

Table 3. Air Quality Index (AQI) values, colour codes, and associated health effects, adapted from (Wambebe & Duan, 2020).

IQA	Health effects	Colours	Level of pollution
0 - 50	Good	Green	1
51 - 100	Acceptable	Yellow	2
101 - 150	Unhealthy for sensitive groups	Orange	3
151 - 200	Unhealthy	Red	4
201 - 300	Very unhealthy	Purple	5
301 - 500	Hazardous to health	Brown	6

3. Results and Discussion

3.1. Average Daily Variation of Atmospheric Pollutants Concentrations

Figure 7 to **Figure 11** present the average daily variation in the concentrations of the different pollutants (NO_2, SO_2, CO, PM10, and PM2.5) at the OIPR site and within the Banco forest.

The average daily concentrations of NO_2 observed at the OIPR site, near the highway are generally higher than those recorded at the Forestry School site (inside the Banco forest) as shown in Figure 7. However, this trend differs on some specific days (March 8th, 14th, 15th, 16th, and 17th, 2021), where the average daily concentrations observed within the Banco Forest exceeded those at OIPR site. These results may be attributed to socio-cultural or sporting events frequently held in the Banco Forest on various occasions (e.g., International Women's Day celebrated on March 8th) and during weekends. The concentrations observed at both sites generally exceed the WHO daily threshold (25 μg/m^3).

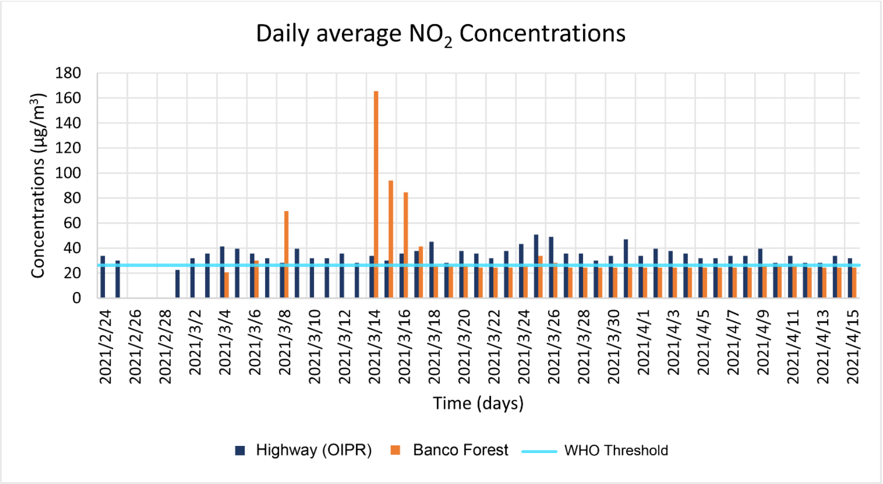

Figure 7. Data collection process Daily average NO_2 Concentrations at OIPR and inside Banco forest from 24th February to 15th April 2021.

The average daily concentrations of CO observed at OIPR site are generally higher than those measured in the Banco Forest as illustrated in Figure 8. This result suggests that carbon monoxide is strongly associated with road traffic. It is important to note that these average daily concentrations remain below the air quality standards set by both the WHO and the national Air Quality Decree.

Regarding sulfur dioxide (SO_2), its daily observed concentrations over both sites are of the same order of magnitude. This result highlights the widespread presence of this pollutant over this area and surrounding, even away from direct pollution sources. It is worth noting that the average daily concentrations exceed both the WHO guidelines and the national air quality standards as shown in Figure 9. The limit value of 125 μg/m^3 as a daily average allowed to be exceeded no more than three (3) times per calendar year was exceeded more than 42 times at OIPR site and 22 times within the Banco forest during the study period. This result highlights the high vulnerability or the exposure of the site located near the highway compared to the site inside the Banco forest to sulfur dioxide (SO_2).

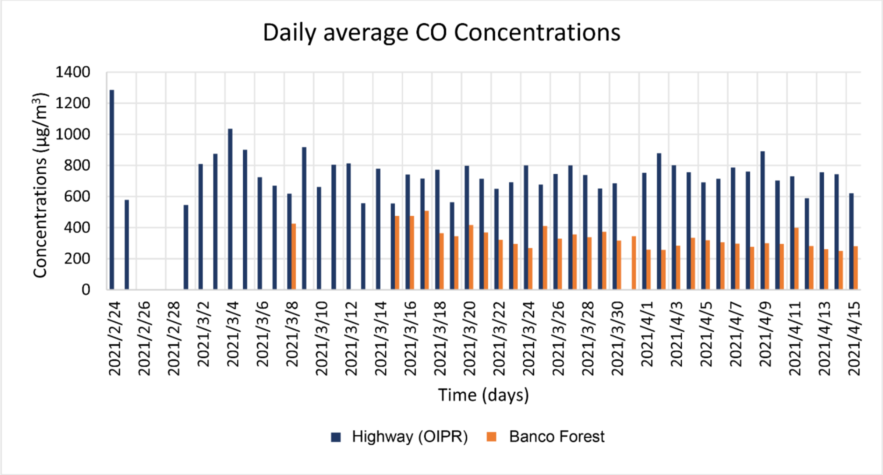

Figure 8. Data collection process Daily average CO Concentrations at OIPR and inside Banco forest from 24th February to 15th April 2021.

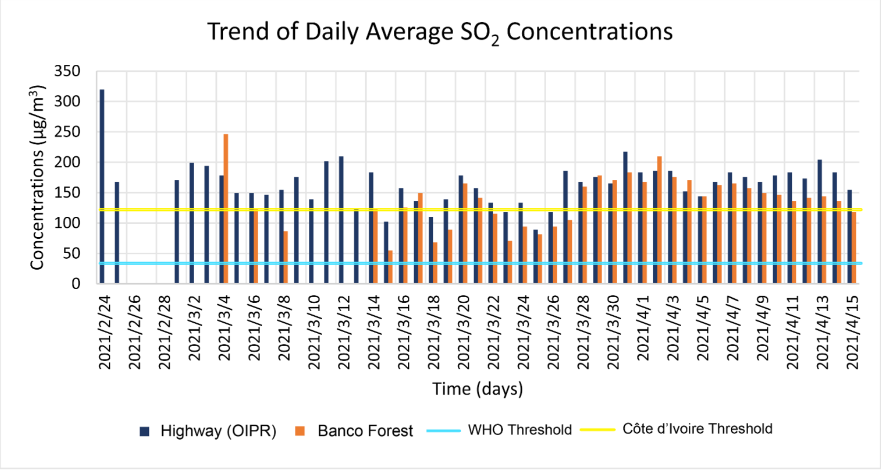

Figure 9. Data collection process Daily average SO_2 Concentrations at OIPR and inside Banco forest from 24th February to 15th April 2021.

Regarding PM10 and PM2.5, the limit values were exceeded between March 31th and April 6th as shown in Figure 10 and in Figure 11, a period that coincides with the Easter holidays, during which there is a significant movement of people from Abidjan to the interior of the country. The limit value of 50 µg/m³ for PM10 as a daily average set by the national Air Quality Decree and not to be exceeded more than 35 times per calendar year was exceeded seven (7) times over 32 days monitoring period. Similarly, the annual limit value of 25 µg/m³ for PM2.5 was exceeded seven (7) times at both monitoring sites.

The results indicate that the daily concentrations of atmospheric pollutants (with the exception of CO) measured at both OIPR and the Forestry School sites exceeded the thresholds recommended by the World Health Organization (WHO) and the national Air Quality Decree. This situation reflects a concerning level of pollution, even in areas presumed to be more protected, such as the Forestry School. The repeated exceedance of daily thresholds at both sites suggests chronic air pollution, which could have long-term health effects on populations who frequently visit the area.

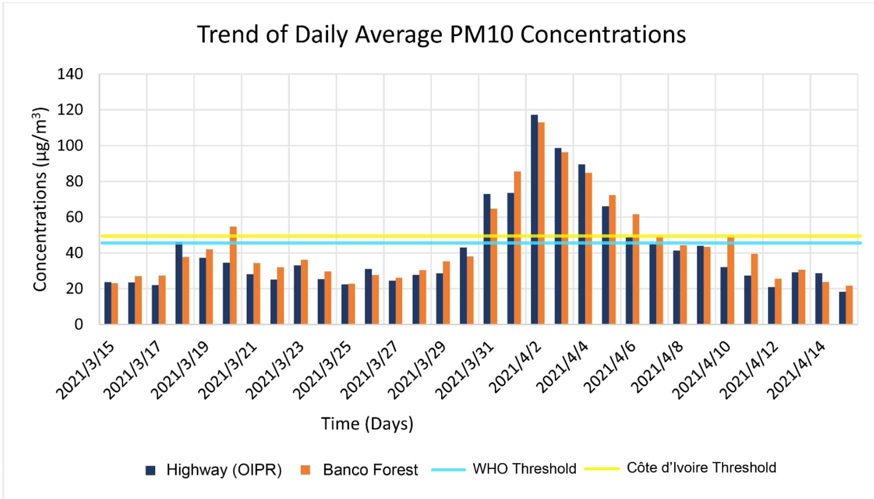

Figure 10. Data collection process Daily average PM10 Concentrations at OIPR and inside Banco forest from 24th February to 15th April 2021.

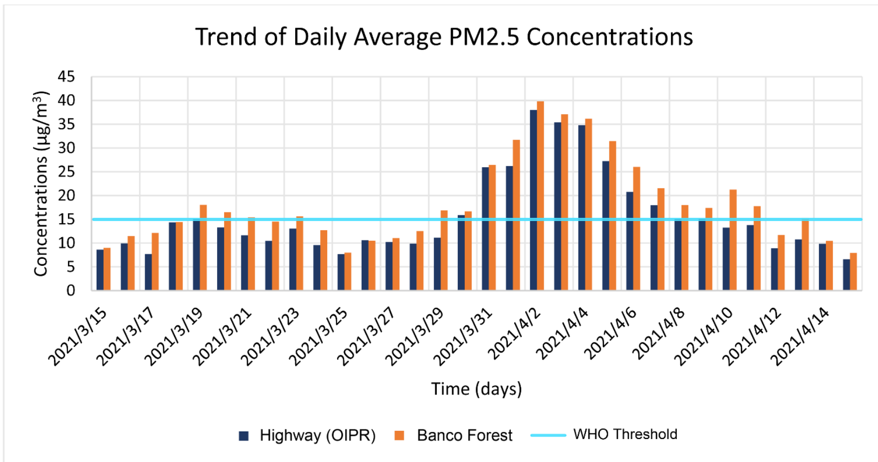

Figure 11. Data collection process Daily average PM2.5 Concentrations at OIPR and inside Banco forest from 24th February to 15th April 2021.

The OIPR site is exposed to heavy road traffic from heavy vehicles using fuel with high sulfur content (Public Eye, 2016), which likely accounts for the particularly high concentrations recorded there. However, the Forestry School site, despite being located in a more vegetated area, also shows pollutant levels above the standards, suggesting the presence of diffuse pollution or nearby sources that impact even so-called protected zones. One such source could be the Yopougon industrial zone, located near the Banco Forest. The Yopougon industrial zone area is the largest in Côte d'Ivoire in terms of surface area (Bahino et al., 2024). There is an incessant flow of large trucks loaded with various products at throughout the day. The vehicles are a major sources of air pollution in this area due to their ages and the lack of maintenance (Doumbia et al., 2021; Bahino et al., 2024). The park is also bordered to the north and the south by former villages of the Ebrié and Attié ethnic groups, with numerous sources of pollution originating from household waste and economic activities. Local residents directly discharge household garbage and wastewater from septic tanks into the park. This is particularly the case in Adjamé, Andokoi, and Abobo borders, where such discharges are significant (Sako et al., 2013).

The comparative analysis reveals that the OIPR site located near the highway exhibits higher levels of pollution, which is consistent with the heavy presence of vehicles and high traffic intensity. However, the occurrence of elevated concentrations at the Forestry School site situated farther from direct anthropogenic pollution sources may be explained by the fact that air pollution is not strictly localized. Pollutants can be transported over distances by wind. According to Kone et al. (2024), wind speeds are highest in Abidjan, which facilitates such transport. Additionally, pollution may originate from multiple and diffuse sources at the urban scale. Indeed, as the Banco National Park is located along the expressway, it is influenced by traffic emissions. The trees canopy slows down the dispersion of pollutants by reducing wind speed, thereby preventing pollutants from dispersing away from lower altitudes, which leads to an increase in pollutant concentrations. Thus, trees may locally limit the dispersion of pollution and consequently increase pollutants concentrations (Nowak & Van Den Bosch, 2018).

Table 4 presents the statistical analysis of daily concentrations of pollutants at the two monitoring sites. For sulfur dioxide (SO_2), the average daily concentrations were 165.98 μg/m^3 and 137.47 μg/m^3 at the OIPR site and the Banco Forest site (Forestry School), respectively, with maximum values of 319.64 μg/m^3 and 246.28 μg/m^3. Both sites recorded concentrations exceeding the World Health Organization (WHO) daily limits as well as those specified by the national air quality decree.

Table 4. Statistical analysis of daily concentrations over monitoring sites.

	Highway (OIPR)					**Banco forest**				
Statistical parameters	**SO_2**	**CO**	**NO_2**	**PM10**	**PM2.5**	**SO_2**	**CO**	**NO_2**	**PM10**	**PM2.5**
Minimum (μg/m^3)	89.08	545.02	22.56	18.26	6.6	55.02	248.46	20.68	21.71	7.95
Maximum (μg/m^3)	319.64	1285.83	50.76	117.19	38	246.28	507.23	165.44	112.92	39.85
Mean (μg/m^3)	165.98	745.34	34.97	40.82	15.57	137.47	336.87	34.46	44.68	18.28
Standard deviation (μg/m^3)	36.42	131.30	5.64	24.47	8.51	41.13	67.57	27.88	23.35	8.73
Coefficient of variation (%)	21.94	17.61	16.13	59.96	54.63	29.92	20.06	80.90	52.26	47.75

Exceedance of the WHO threshold, Exceedance of the air quality decree threshold of Côte d'Ivoire.

Regarding carbon monoxide (CO), the average daily concentrations observed during the study period were 745.34 μg/m^3 at the OIPR site and 336.87 μg/m^3 at the Forestry School site. Although relatively high, these concentrations remained within the acceptable standards.

For nitrogen dioxide (NO_2), the average daily concentrations recorded were 34.97 µg/m^3 and 34.46 µg/m^3 at the OIPR and Forestry School sites, respectively. While these concentrations are similar, they exceed the WHO guideline value of 25 µg/m^3.

In the case of PM10, the average daily concentrations were 40.82 µg/m^3 and 44.68 µg/m^3 at the OIPR and Forestry School sites, respectively. These values fall within the same range and are below both the WHO (45 µg/m^3) and national (50 µg/m^3) threshold values.

Finally, for PM2.5, the average daily concentrations were 15.57 µg/m^3 at the OIPR site and 18.28 µg/m^3 at the Forestry School site. These values are in the same range but clearly exceed the WHO limit of 15 µg/m^3, indicating a potential health risk at both sites. Indeed, short-term exposure to PM2.5 can have a delayed effect on respiratory tract inflammation and lung function, with the impact being more pronounced in individuals already vulnerable to respiratory conditions (Buthelezi et al., 2024).

Table 5 presents a comparative overview of daily air pollutant concentrations (PM10, PM2.5, SO_2, NO_2 and CO) from various studies conducted in different urban and forested environments across Africa and Asia.

The Banco forest and OIPR sites in Côte d'Ivoire (this study) show relatively low PM concentrations compared to other Ivorian sites in Abidjan and Korhogo, where PM10 concentrations levels can reach over 500 µg/m^3. In contrast, forest sites in Malaysia such as Bangi forest and Buvit Nanas forest also exhibit low PM values, reinforcing the role of vegetation in reducing particulate pollution. Concerning SO_2 and NO_2 concentrations, SO_2 levels at the OIPR site (165.98 µg/m^3) are higher than those in the Banco forest (137.47 µg/m^3), likely due to traffic influence. NO_2 values are nearly identical between the two sites around 34.5 µg/m^3 suggesting a common urban source such as nearby roads, industrial zone. A significant disparity in CO concentrations levels is observed: 745.35 µg/m^3 at OIPR compare to 336.87 µg/m^3 in Banco forest. This supports the assumption that traffic emissions are the dominant source of CO. Extremely high CO values (e.g., 9978.9 µg/m^3 in Nigeria) highlight severe pollution conditions in some urban centers. Urban sites such as Dakar, Abuja and Accra report a wide range of pollutant concentrations, some of which exceed WHO recommended limits. Forest areas, regardless of country, consistently display lower pollutant concentrations, demonstrating their function as pollution buffers compare to urban sites. The table illustrates a clear contrast between pollution levels in urban traffic-affected sites and forested or natural environments. The findings from Banco forest and OIPR confirm that proximity to human activity, especially vehicle traffic, significantly influences air quality. Moreover, comparing African and Asian sites emphasizes the global relevance of green spaces in mitigating air pollution.

Table 5. Daily air pollutants concentrations compare to others studies.

	Daily air pollutants concentrations (μg/m³)					
Site, country	**PM10**	**PM2.5**	**SO_2**	**NO_2**	**CO**	**References**
Banco forest, Côte d'Ivoire	44.68	18.28	137.47	34.46	336.87	This study
OIPR, Côte d'Ivoire	40.82	15.57	165.98	34.97	745.34	
Abidjan, Côte d'Ivoire		4.2 - 93.3				(Bahino et al., 2024)
Accra, Ghana		5.4 - 122				
Abidjan, Côte d'Ivoire	38.1 - 160.4	23.8 - 113.4				(Gnamien et al., 2021)
Korhogo, Côte d'Ivoire	212.2 - 534.7	57.4 - 230.4				
Dakar, Senegal	120 - 180*	25 - 48*				(Sow et al., 2021)
Abuja Municipal Area, Nigeria		15.3 - 70.20				(Wambebe & Duan, 2020)
Calabar, Nigeria	170 - 260		0.04 - 0.15 ppm or 104.4 - 91.5	0.02 - 0.09 ppm or 37.74 - 169.83	3.3 - 8.7 ppm or 3785.1 - 9978.9	(Abam & Unachukwu, 2009)
Buvit Nanas Forest (Malaysia)	13.44 site 1 17.91 site 2 20.23 site 3					(Norela et al., 2010)
Non-urban Bangi forest (Malaysia)	4.27					

NB: *Average monthly concentrations.

3.2. Average Hourly Air Quality Index (AQI)

Figure 12 shows the average hourly profile of the Air Quality Index (AQI) over the entire study period, from February 28th to April 15th. On average, the AQI is considered acceptable ($50 < AQI < 100$) at both sites. In the Banco Forest, air quality is generally degraded between 5:00 a.m. and 7:00 a.m., then begins to improve (with a gradual decrease in AQI) from 7:00 a.m., reaching its minimum value (40) at around 5:00 p.m. After 5:00 p.m., air quality begins to deteriorate again.

At the OIPR site (near the northern highway), the AQI remains nearly constant (around 58) between midnight and 8:00 a.m. The AQI rises from 8:00 a.m., peaking at approximately 66 around 9:00 a.m., then decreases between 10:00 a.m. and 12:00 p.m. from 12:00 p.m. onward, air quality progressively worsens, reaching its highest value (approximately 73) at 7:00 p.m. as shown in Figure 12.

The hourly variation in the Air Quality Index (AQI) is consistent with the process of photosynthesis, during which plants absorb oxygen and release carbon dioxide at night, and conversely release oxygen and absorb carbon dioxide during the day. The poor air quality observed at both sites is generally attributed to

PM2.5, PM10, and SO_2, as these pollutants consistently exhibit the highest (i.e., worst) individual air quality index values.

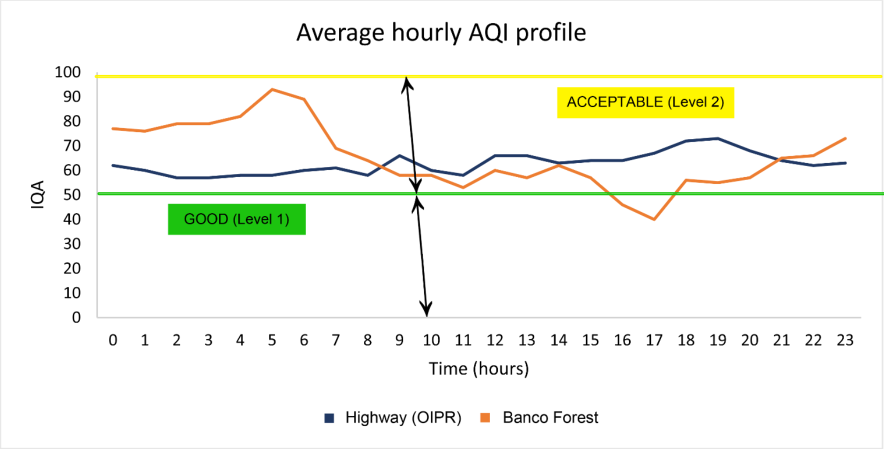

Figure 12. Comparison of average hourly AQI variability profile for both monitoring sites during the study period.

The average daily Air Quality Index (AQI) was generally acceptable during the study period, from February 28th to April 15th, 2021, except the period from March 30th to April 4th as shown in Figure 13, which included the weekend of the Easter celebrations.

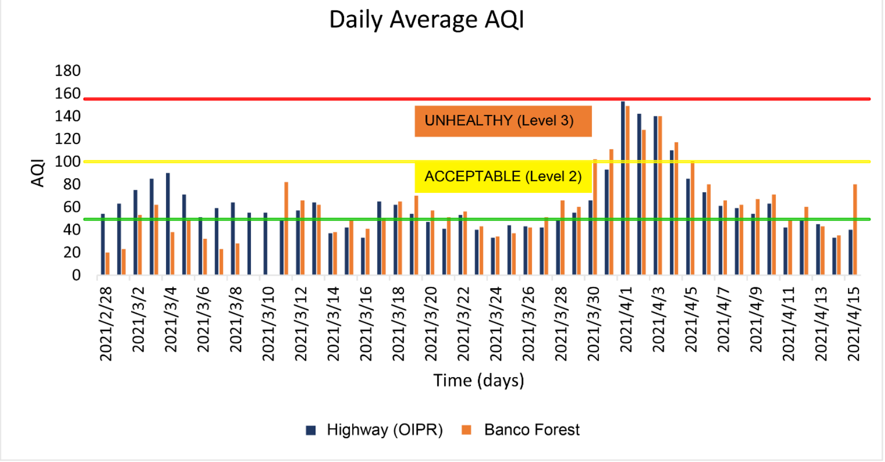

Figure 13. Average daily AQI trend monitoring sites during the study period.

During this interval, air quality was classified as poor (100 < AQI < 150) at both sites, with AQI values of similar magnitude (see Table 6). This result highlights the extent of air quality degradation in the study area.

This deterioration can be attributed to the increased traffic on the northern highway as well as socio-cultural events frequently held during public holidays in Banco Forest. Banco Forest is one of the most visited tourist sites in Abidjan.
The data presented in Table 6 show that the measurements taken at the OIPR site near the northern highway and those from Banco forest are of the same order of

magnitude. This result may be attributed to natural pollutant emissions from Banco forest that add to anthropogenic emissions, as well as the long-range dispersion of air pollutants. Indeed, trees release various chemical substances, including volatile organic compounds (VOCs), which can contribute to air pollution (Sharkey et al., 1991; Guenther, 2002; Nowak & Van Den Bosch, 2018). According to Tingey et al. (1991), the oxidation of VOCs accounts for a significant portion of the global carbon monoxide (CO) budget. Moreover, VOCs emitted by trees can also promote the formation of tropospheric ozone (O_3) and fine particulates matter (Sharkey et al., 1991; Nowak & Van Den Bosch, 2018).

Table 6. Statistical analysis of AQI over the monitoring sites.

	Highway (OIPR)	Banco forest
Maximum	153	149
Minimum	33	20
Mean	**63**	**62**
Standard deviation	27.33	30.38
Coefficient of variation (%)	43.38	48.99

3.3. Consequences of Air Pollution in a Natural Reserve

Trees in parks and reserves remove gaseous air pollutants primarily through absorption via the stomata of their leaves, but they also capture certain gases on the surface of the plant. In addition, they have a direct effect on atmospheric particulate matter by intercepting particles that are deposited on the plant surface (Nowak & Van Den Bosch, 2018; Nowak & Heisler, 2010). However, the exceedance of pollutant concentration thresholds observed in this study will have not only health consequences for visitors to the site, but also detrimental effects on tree foliage. Indeed, as demonstrated by Zamblé Fidèle (2020), these exceedances of threshold concentrations of various air pollutants may damage sensitive biological resources in natural areas, and could alter the spectral and biochemical properties of trees foliage in the Banco Forest. For example, in the case of sulfur oxide (SO_2) pollution, the reducing properties of this gas can disrupt the functioning of the photosynthetic apparatus by degrading chlorophyll (Percy & Karnosky, 2007). Indeed, according to (Kardel et al., 2010**)**, prolonged exposure of plant leaves to air pollutants can lead to their degradation, including the destruction of the epicuticular wax layer on the leaf surface, thereby increasing leaf wettability (i.e., the ability of the leaf surface to be wetted by water) (Zamblé Fidèle, 2020). Chlorophyll content in leaves was higher in parks and gardens than along roadsides, in industrial areas, and in residential zones across all species (Zamblé Fidèle, 2020). This finding suggests that vegetation growing in less polluted environments tends to maintain better photosynthetic activity and overall physiological health. In contrast, the lower chlorophyll content observed in areas with higher levels of anthropogenic pollution may reflect damage to the photosynthetic apparatus due to the oxidative and acidifying effects of atmospheric pollutants such as NO_2, SO_2, and particulate matter. These stressors can degrade chlorophyll molecules and disrupt key metabolic processes, ultimately affecting plant growth and ecosystem functioning. Thus, chlorophyll content can serve as a useful bioindicator for assessing the impact of air quality on urban vegetation. Previous studies (Ninave et al., 2001; Mir et al., 2008) estimate that heavy automobile traffic leads to a decrease in chlorophyll content in plants along roadsides. Indeed, a large amount of particulates matter on the leaf surface hinders chlorophyll synthesis due to the presence of several heavy metals (Pb, Cu, Cd, etc.) and polycyclic hydrocarbons, which inhibit the enzyme necessary for chlorophyll synthesis (Zamblé Fidèle, 2020). Moreover, the deposition of particulate matter, by damaging the pores of the stomata, affects the availability of light to the plants, which is essential for photosynthesis (Zamblé Fidèle, 2020). Air pollutants enter the leaf tissues through the stomata and cause partial destruction of the chloroplasts as well as a decrease in pigment content in the cells of the polluted leaves (Zamblé Fidèle, 2020; Keller, 1986).

4. Conclusion

This study was conducted from February 24th to April 15th, 2021, at two distinct sites: the Banco Forest and the North Highway, within the perimeter of the Ivorian Office of Parks and Reserves (OIPR). Its objective was to assess atmospheric pollution levels by identifying the main sources, and examining the environmental and health implications. The results show that although the Banco Forest is commonly recognized as an ecological buffer zone that promotes air depollution, it can also act as an accumulation area for atmospheric pollutants. This situation is mainly due to the reduction in wind speed caused by the dense vegetation cover, which limits the dispersion of pollutants. The analysis of daily average concentrations of sulfur dioxide (SO_2), suspended particles PM10 and PM2.5 reveals levels significantly above the regulatory thresholds set by the national air quality decree and the recommendations of the World Health Organization (WHO). These exceedances expose sensitive populations (notably children, the elderly, and asthmatic individuals) who regularly visit the site to increased health risks. Furthermore, physiological alteration of vegetation, particularly a reduction in leaf chlorophyll content, may result from this persistent atmospheric pollution.

The study highlights a temporal variability in air quality, closely correlated with the time of day and the intensity of human activities. The main contributors to air quality degradation identified at these sites are fine particles (PM2.5, PM10) and sulfur dioxide (SO_2). The results also highlight a consistent trend across forested and less anthropized environments exhibit significantly lower air pollutant concentrations than urban and traffic-impacted areas. The case studies of Banco forest and OIPR confirm that proximity to anthropogenic sources, particularly vehicular traffic, plays a major role in air quality degradation. The comparative assessment between African and Asian sites reinforces the global importance of preserving green spaces as effective buffers against urban air pollution and as integral components of sustainable urban planning.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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