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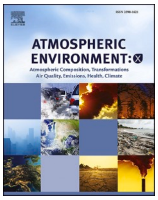

Central parks as air quality oases in the tropical Andean city of Quito

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ABSTRACT

Urban ecosystem is an intricate agglomeration of human, fauna and flora populations coexisting in natural and artificial environments. As a city develops and expands over time; it may become unbalanced, affecting the quality of ecosystem and urban services and leading to environmental and health problems. Fine particulate matter (particulate matter with aerodynamic diameter ≤2.5 μm - $PM_{2.5}$) is the air pollutant posing the greatest risk to human health. Quito, the capital city of Ecuador, exhibits a high occurrence of exposure to unhealthy levels of $PM_{2.5}$ due to a combination of natural and social variables. This study focused on three central parks of this high elevation city, investigating the spatial distribution of $PM_{2.5}$ concentrations. The particle pollution was then modeled using Normalized Difference Vegetation Index (NDVI). Hazardous instantaneous levels of $PM_{2.5}$ were consistently found on the edges of the parks along busy avenues, which are also the most frequented areas. This raises concerns about both short- and long-term exposures to toxic traffic pollution in recreational areas within urban dwellings in the global south. The NDVI model successfully predicted the spatial concentrations of $PM_{2.5}$ in a smaller urban park, suggesting its potential application in other cities. However, further research is required to validate its effectiveness.

1. Introduction

An urban ecosystem is a complex cluster of human, fauna and flora populations cohabiting in both natural and artificial environments. Development and expansion of cities may become disproportionate over time, especially in developing countries due to illegal invasions, lack of or attention to regulations, generating environmental and health problems (Higueras, 2009). At this point in time, urban areas accommodate progressively more than half of global human population and generate over two-thirds of the world's gross domestic product (World Bank, 2021). As cities condense most of the material and intellectual production for a specific region, they create the majority of anthropogenic atmospheric pollution from mobile (e.g., transportation) and fixed emission sources (e.g., industries) (Limb, 2016).

Currently, anthropogenic emission sources heavily rely on fossil fuels, resulting in the production of hazardous gaseous pollutants (e.g., nitrogen oxides, carbon monoxide, unburned hydrocarbons, sulfur dioxide, volatile organic compounds, etc.) and particulate pollutants (e.g., dust particles, combustion fumes, aerosols, etc.). The particulate matter with aerodynamic diameter ≤2.5 μm ($PM_{2.5}$) are fine particles, often with toxic chemical composition (e.g., soot, heavy metals, etc.), that enter human body and are deposited in the deepest parts of the respiratory system able to filter into the bloodstream with very little possibility of being expelled (EPA., 2003). Exposure to $PM_{2.5}$ can affect respiratory and cardiovascular systems causing premature death, heart attacks, irregular heartbeat, decreased lung function and aggravated asthma, irritation of the airways, coughing or difficulty breathing, and are especially hazardous to risk populations (EPA., 2003; Patrick, 2016; Pope et al., 2019; United States Environmental Protection Agency, 2021).

As a result, air pollution, predominantly PM, leads to millions of premature deaths annually, affecting 99% of the global population that breathes poor air quality (Limb, 2016; WHO, 2014; World Health Organization, 2022). In response to this problem, urban development must adapt and transform, partially trusting the mitigating power of green areas, due to their ecological functions. Thus, when considering life quality of urban population, city parks, forests or gardens may serve as air pollution filters and air quality oases. Research indicates that parks

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and green spaces in cities play a fundamental role, not only by providing means of recreation for the well-being of citizens (Branas et al., 2011; Lee et al., 2015) but also by contributing to the conservation of aquifers, reducing temperature, noise, runoff and levels of toxic particles in their vicinity (Arthur and Hack, 2022; Cohen et al., 2014; Klingberg et al., 2017; Pataki et al., 2021; Sinharay et al., 2018; Viippola et al., 2018; Xing et al., 2019; Xing and Brimblecombe, 2020a, 2020b). Since all previous research comes from developed countries, it is relevant to understand how air quality would be reflected in urban parks in the cities of the Global South.

It's worth noting that there is global inequity, in terms of socioeconomic status and racial-ethnic disparities, in accessibility to a number

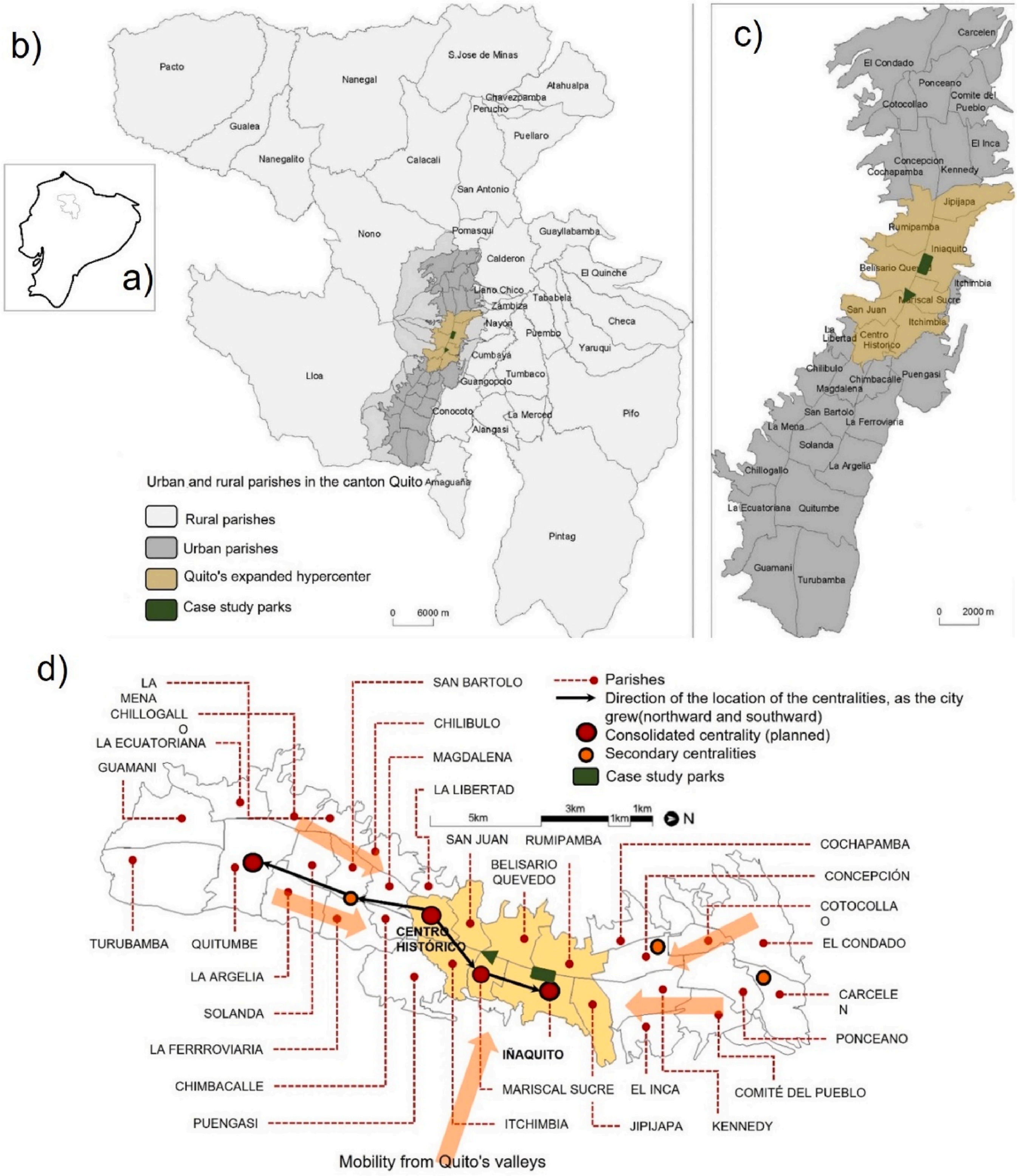

Fig. 1. Urban and rural parishes of Metropolitan District of Quito (a), Ecuador (b). Study sites – urban parks (marked in green) in the city of Quito (c). Panel d) shows the population circulation towards the central parts of the city and urban growth towards the north and south of the city.

and quality of urban green spaces. This results in notable differences in both the benefits to human physical and mental health and the ecosystem services provided by urban green spaces (Rigolon et al., 2018). In Latin America, the rapid growth of cities, accompanied by poor planning, has prevented an adequate distribution of urban green spaces relative to the size and density of cities (Sedrez, 2013). A study from Santiago, Chile, reported that richer districts of the city had higher leaf area index, compared to the poorer districts, directly influencing air quality (Escobedo and Nowak, 2009). In addition, there is a greater utilization of parks categorized as central parks compared to urban parks in peripheral neighborhoods (Moran et al., 2020, 2022). This preference is largely attributed to the availability of diverse leisure or sports activities, as well as considerations of safety and accessibility. However, the question remains: Do these parks have adequate environmental quality? Different areas of central parks may offer different air quality, due to the levels of pollution generated by the nearby roads and the proximity of some recreational or sport activities to these roads. Again, while there are some studies analyzing air quality of urban parks, all of them originate from developed countries, where strict fossil fuel standards and high quality technologies are applied, resulting in reduced urban air pollution (United States Environmental Protection Agency, 2018). Additionally, while some research focuses on park infrastructure, to the best of our knowledge, none uses the Normalized Difference Vegetation Index to assess vegetation quality or density in relation to air pollution. Here, we present a study on the spatial distribution of $PM_{2.5}$ concentrations and their correlation with the NDVI index, which is used to model air quality in three of the most visited central parks in Quito, Ecuador. Due to their urban accessibility, these recreational areas might offer inadequate air quality, necessitating potential changes in traffic strategies or park design to avoid visitors' exposure to toxic pollution. This work sheds light on the urban quality of life in a developing country and lays the foundations for improving urban greening strategies worldwide.

2. Methodology

2.1. Study site

Ecuador is located on the equatorial line in the northwestern part of South America (Fig. 1). With a territorial extension is 256,370 km^2 (United Nations Development Program, 2022), Ecuador is a highly biodiverse country due to a variety of regions, ranging from the Andean mountains and Amazonian jungle to the Pacific Ocean coast and the Galapagos archipelago. Ecuador shares borders with Colombia and Peru. Its high-elevation capital, Quito, is located in the Andean region at 2850 m above sea level (m.a.s.l.) (see Fig. 1a–c) and houses 2.6 million people (Instituto Nacional de Estadísticas y Censos (INEC)., 2013). Ecuador, while a decade ago was positioned as high-middle income country has been in the last few years experiencing an economic crisis and rapidly increasing violent crime and poverty rates (i.e., 38% of the population living in multidimensional poverty) (Sosa et al., 2023; World Bank, 2023).

When studying montane cities, it becomes clear that their spread and urban mobility can be remarkably constricted by abrupt changes in the surrounding terrain (Virtudes et al., 2017). These unusual conditions often exacerbate air pollution problems due to a concentration of population activity concentration in certain parts of the city, bottlenecking transport circulation (i.e., connectivity through tunnels, bridges, etc.), mixing height restrictions, and blocked ventilation, among other factors (Bell et al., 2006; Mwaniki et al., 2014; Zalakeviciute et al., 2012). This is precisely the case of Quito, Ecuador. This high-elevation city is founded on the eastern wall of an active volcano, Pichincha (4800 m. a.s.l.), and is disproportionately long (extending over 40 km North-South) and narrow (varying from 3.5 to 15 km East-West). The narrowest part of the city is the central area (Fig. 1c and d). Along the cross sections of the city, some parts are developed on steep slopes, while very limited parts are located on level terrain. Due to this irregular topography, many parts of the city are developed within a high-gradient landscape, with streets having gradients of up to 23% (23 m height increase every 100 m). During clear mornings, air pollution follows the terrain and collects in the lower zones of the city, creating a visible layer of smog. It's worth noting that the metropolitan area is wider than Quito district and spreads beyond this mountain 'balcony' into the nearby lower elevation valleys (2300–2800 m. a.s.l.) towards the eastern side of the inter-Andean valley (Fig. 1b).

As the city rapidly grows, the density also increases, especially in the central parts of the city (Fig. 1c and d). Previously private family houses and gardens are swiftly replaced by the high-rise apartments and office buildings. This creates an increased flow of private vehicles and public transportation to and from those areas, resulting in traffic jams during various hours of the day, including weekends (Fig. 1d). Poor-quality fuel and vehicle maintenance, erratic driving style, and the lack of oxygen (~70% of available oxygen), contribute to elevated levels of air pollution in most parts of the city (Zalakeviciute et al., 2018a, 2018b). In addition, high-rise buildings usually contain garage spaces below the surface, preventing the development of trees near them. Moreover, towards the outskirts of the city, any undeveloped green space might be legally or illegally constructed. Illegal invasions are quite common in Ecuador.

In Quito, green spaces are limited to mostly substantial central city parks designated for various recreational, educational or commercial activities. To help the population access these central parks, offices and shopping centers, diesel-powered bus lines run along the borders of the parks along big avenues. This, in effect, creates atmospheric pollution originating from heavy public or commercial and light private transportation.

2.2. Data collection and analysis

$PM_{2.5}$ pollution scans were performed using a portable real-time CEL-712 Microdust Pro™ monitor (Casella., n.d.) coupled with a GPS (Garmin, 2011). The near-forward angle light scattering Microdust Pro was calibrated using a zero-air and a known concentration (164 mg m^{-3}) filters to set the zero and the span, prior to the sampling. In addition, the portable particle sensor was validated by collocating it with Thermo Scientific 5014i Beta Continuous Ambient Particulate Monitor ($R^2 = 0.74$) prior to the experiment, a technique previously described in other studies (Hernandez et al., 2019; Hernandez et al., 2020a, 2020b). The Microdust Pro and the GPS were synchronized to record GPS coordinates and average $PM_{2.5}$ concentration data at 10-s interval. The $PM_{2.5}$ sensor was positioned at the height of 1.5 m, pointing the inlet forward while walking at an approximate speed of 2 km h^{-1} on sidewalks or park paths. This height was chosen to approximate the sampling height towards the average human mouth and nose (Roser et al., 2013). The samplings were performed during the morning rush hours (8:00–10:00 a.m.), as this period of time of the day is considered the least atmospherically dynamic and anthropogenically active time in Quito in terms of pollution changes and shows the worst air quality conditions (Zalakeviciute et al., 2020). Thus, these data would contribute to the most conservative urban pollution scenario. The samplings for La Carolina Park were performed on July 6, 2022, and for El Ejido and La Alameda parks July 7, 2022.

Pollution data collected from each urban park were combined to produce spatial distribution maps for each study area. Outlier data resulting from equipment misreading were eliminated (Rohde and Muller, 2015). The assumptions to execute spatial interpolation methods were verified, with special attention to data normal distribution. Due to the spatial characterization of the study area, which featured dense sampling and relatively regular distribution, the Inverse Distance Weighted (IDW) interpolation method was used. This method determines cell values through a linearly weighted combination of the sample set (Sajjadi et al., 2017). The best results of this method are obtained when the sample is dense enough with respect to the local variation it attempts to simulate (Watson and Philip, 1985), so its reliability is high for the study area and our sampling system. It allowed us to obtain several continuous maps with information on the weighted mean distance of $PM_{2.5}$.

Visiting population concentration estimate was performed by a direct count at different parts of the parks, especially focusing on the main intersections (Lipovská and Štěpánková, 2013). It was performed during the morning rush hours from 8:00 a.m. to 10:00 a.m. on December 11 (Carolina Park) and 12 (El Ejido and La Alameda), 2023. The park visitors' "number" was categorized into four groups: high count (more than 10 people in a 50 m radius), medium high count (7–10 in a 50 m radius), medium low count (3–6 in a 50 m radius) and low count (2 or less in a 50 m radius).

Finally, typical morning traffic for the study areas was obtained from Google Maps Traffic layer, by selecting the 8–10:00 a.m. traffic conditions along the main avenues bordering the three studied parks. Traffic conditions are represented by a traffic light color scale: red – very slow-moving traffic; orange/yellow – slow-moving traffic; green – fast-moving traffic.

2.3. *Normalized Difference Vegetation Index analysis*

To study the relationship between urban air quality and the quality and density of park vegetation, we derived the Normalized Difference Vegetation Index (NDVI). This index, commonly used for vegetation monitoring from spatio-temporal approaches (Bonilla-Bedoya et al., 2020; Myneni et al., 1995), was obtained from an image of the SPOT 7 sensor of the Airbus satellite: SPOT 7 PMS 1,512,376, ORT 2956433101 (Bonilla-Bedoya et al., 2021).

To elucidate the relationship between $PM_{2.5}$ spatial concentration and NDVI, we ran a Geographically Weighted Regression (GWR), a local technique for exploring spatial heterogeneity in data relationships (Lu et al., 2014). The starting point is a simple linear model:

$$y_{i=B_0+B_1 x_i+\varepsilon_i}$$

The relationship between y ($PM_{2.5}$) and x (NDVI) is assumed to be constant across the study area, at every possible location in the study area the values of B_0 and B_1 are the same. The residuals from this model ε_i are assumed to be independent and normally distributed with a mean of zero (Harris et al., 2010).

2.4. *Cross-sectional analysis*

A Digital Elevation Model (DEM), commonly employed in air quality modeling (Diaz-de-Quijano et al., 2014), was utilized in this study. The DEM data were obtained from the open-access NASA Earth Data website (https://www.earthdata.nasa.gov/) of Alaska Satellite Facility (ASF) on the earth data web. These data are widely used due to their levels of accuracy and applications (Polidori and El Hage, 2020). Complementary information such as main roads, urban area and park areas were obtained from the Geoportal of Ecuador, a compendium of geospatial data.

To showcase the profile variability in the Andean city terrain, five transversal cuts were generated. Each cut initiated from a common point on the Pichincha volcano – the highest elevation in the area (4800 m. a.s.l.), then traversing through the main parks of the city towards the valleys in the East. The terrain profiles were determined using the 3D analysis tool 'Elevation Profile'.

The map was built using ArcGIS PRO. The first layers added were the DEM and RGB raster, followed by the urban and parks areas. The main roads layer was crucial for highlighting, as the transport sector is the principal source of pollutants in the city (Zalakeviciute et al., 2018b). The map makes it clear that the main parks are surrounded by some of the busiest roads with heavy Quito traffic.

3. Results and discussion

3.1. *Terrain effect on urban infrastructure in high elevation city*

The current urban planning instruments of Quito, the high-elevation Ecuadorian capital, define a polycentric urban model. Depending on the role and scale of each district, this model creates a system of centralities divided into centers and micro-centers. However, the expanded hypercenter, remaining the focal point, is crucial for important urban mobility from the peripheries of the city (Fig. 1d). Simultaneously, this section of the elongated Andean city is also the narrowest (refer to Fig. 2, Profile 4). Consequently, it requires enough major avenues and highways to accommodate the daily commute of the population, connecting the city from north to south and to the valleys to the east. As a result, the central part of the hypercenter, enclosed by the Metropolitan hill to the east and the Pichincha volcano to the west, exhibits a high density of extremely busy roads, generating the largest emissions from mobile sources in the region (Fig. 2).

As seen in Fig. 2, Quito's complex morphological setting has resulted in flat areas being the locations with the greatest variety of activities, including economic, mobility infrastructure, sports, educational, healthcare, governmental, hospitality, services and consumer goods. The hypercenter, composed of six parishes including the UNESCO-listed historical center (Centro Historico in Spanish; Fig. 1d), concentrates the highest quantity and diversity of productive factors (Herrero-Olarte and Díaz-Márquez, 2020). Due to the terrain complexity, some of Quito's main urban parks are established on horizontal terrain (Fig. 2, marked by "x" in cross-sectional lines). However, there are also green spaces located on naturally preserved hills and undeveloped, unlivable high-level slopes such as Metropolitan Hill (Fig. 2, Profile 3). In the case of the two studied zones, La Carolina (marked in orange, Fig. 2, Profile 3), and El Ejido/La Alameda parks (marked in yellow/pink, Fig. 2, Profile 4), there is very little horizontal area for urban development. This implies that the main transport circulation must be planned in a rather limited space, and thus near the central parks, to accommodate continuous north-south commuting for the urban population.

As the Andean topography is very complex, it is also important to understand the topography of a city because of the direct impact of the terrain on the dispersion of pollutants (Antonić and Legović, 1999). Apart from hectic and unsafe driving, common in Latin America (Martinez et al., 2019), terrain complexity might affect urban driving styles and consequent particulate matter emissions from increased acceleration or breaking (Lough et al., 2005). Additionally, in Quito, it helps to understand why many of the main avenues are aligned in the same direction, concentrating vial infrastructure in a small area. Visualizing the elevation profiles in this urban area (Fig. 2) can help understand the dynamics of daily commute in a montane city.

3.2. *p.m.$_{2.5}$ spatial distribution in three urban parks*

Fig. 3b,c,e,f,h, i indicate that near the boundaries of the three studied urban parks in Quito, when adjacent to busy roads (typical Google Traffic marked by red color on morning rush hour 8–10:00 a.m. on a workday), short-term particulate pollution can reach extremely high concentration peaks (up to 1.1–2.47 mg m^{-3}). Though these $PM_{2.5}$ values may seem extremely high, they are short-term (10-s average) concentrations, and the measured maximum level range compares well to indoor air quality levels, reported by a recent experimental study on suspended particles (Benabed and Boulbair, 2022). In our study high peak concentrations are due to the fact that the quality of fossil fuels used for public and private transportation is of Euro 1–2 standards for diesel and Euro 2–3 standards for gasoline cars (Zalakeviciute et al., 2018b). On top of that, to adapt to the high sulfur content in diesel and gasoline, new vehicles imported to the country are of those older technologies (or are technically adjusted to function with these fuels). To make things worse, there is a lack of implementation of regulations for

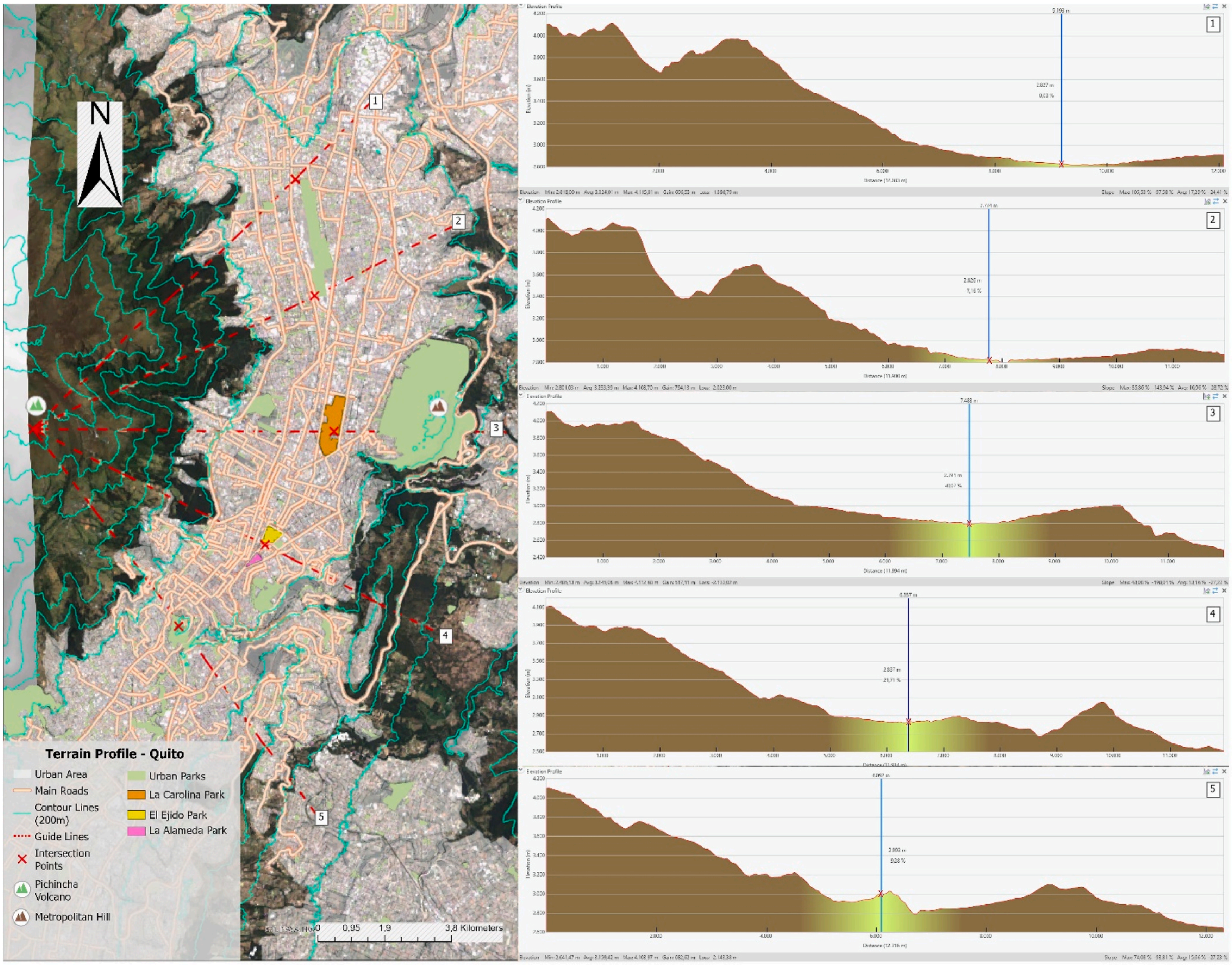

Fig. 2. Quito city map and location of main urban parks: La Carolina (marked orange on Profile 3) and El Ejido/Alameda parks (marked yellow/purple on Profile 4).

proper technical review or maintenance (i.e., lack of funds or education), which, in turn, is often done improperly or unethically (i.e., only for the time to pass technical revision). The local conditions of lower oxygen (i.e., 70% if compared to sea level) content due to the elevation (~2850 m. a.s.l.) also add to reduced combustion efficiency. Finally, hectic driving style further contributes to inefficient fuel use, especially on main avenues due to the possibility to develop high speeds (e.g., buses racing with each other). Rush hour traffic jam (red color on Google Traffic) implies an increased acceleration and breaking of the transport. As a result, in the studied areas where two major avenues intersect, personal exposure to elevated $PM_{2.5}$ concentrations is possible (Fig. 3b, c,e,f,h,i). At the same time, these are the zones where a lot of people circulate, due to the intersection of a number of main paths in these rather central business areas (Fig. 3c–f,i). In case of continuous or repeated park use, long-term health effects are possible as well.

Spatial distribution of $PM_{2.5}$ concentrations in three studied Quito parks also indicates that particle pollution decreases towards the centers of the parks (1–22 μg m^{-3}), most likely by filtering through the park vegetation (Cohen et al., 2014; Pataki et al., 2021; Viippola et al., 2018; Xing et al., 2019; Xing and Brimblecombe, 2020a). Thus, the central parts of the parks offer cleaner air and may serve as a refuge from toxic motorized vehicle exhaust (Fig. 3c–f,i). This is a crucial finding, as one might assume that park grounds are a healthy green space; however, the air on its peripheries is as polluted as on a street. Here we refer to a recent study reporting no health benefits when walking on sidewalks of a busy street in London, in contrast to that of a city park (Sinharay et al., 2018). However, according to our findings, a path in a central park close to traffic may not offer intended health benefits when considering a developing country (Fig. 3b–e,h). However, the reason why most people may choose to walk or exercise on the outside, rather than deeper inside the park, is safety in this increasingly more unsafe city (Sosa et al., 2023). It is quite interesting that while $PM_{2.5}$ pollution is lower inside the park, so is the concentration of visitors, raising a rather intriguing issue to light (Fig. 3).

Apart from considering the bordering avenues, it may seem that the density of the number of avenues in a specific area might play a role as well. For instance, La Carolina park, situated in the business center, is surrounded by five major avenues from the west and three from the east within a radius of 1.5 km (Fig. 3b and c and Fig. 2, Profile 3). High $PM_{2.5}$ concentrations are more consistent in this area, in comparison to the other two studied parks. The second study area, including two city parks El Ejido and La Alameda, is surrounded by four major avenues within 1 km radius (Fig. 3f–i and Fig. 2, Profile 4). The air quality overall is better in this latter area, with the exception of a few spots near highly polluted major avenues with heavy bus traffic in the southern rim of the El Ejido park (Fig. 3f) and northern rim of La Alameda Park (Fig. 3i).

The findings of this study are of noteworthy concerns regarding short-term exposure to toxic exhaust from the city traffic, especially for

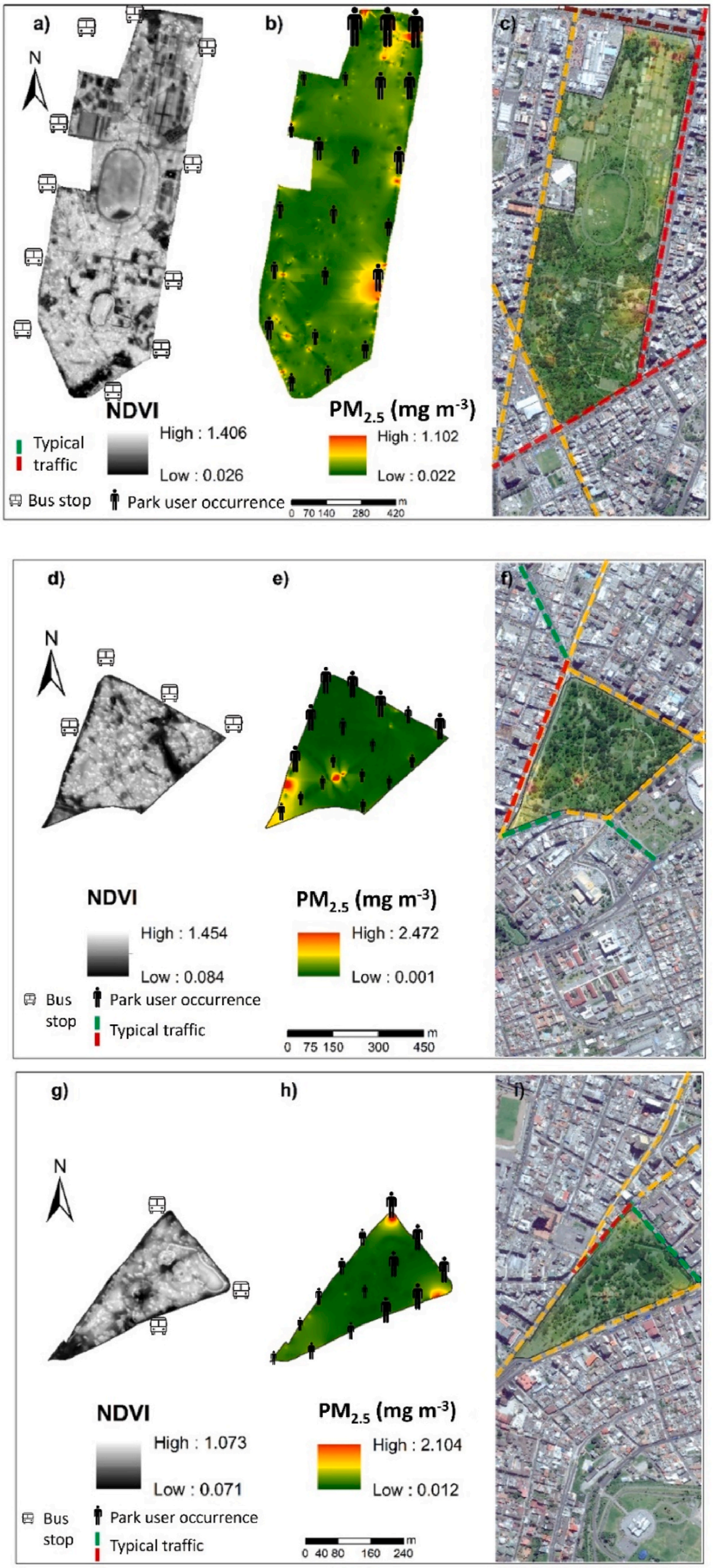

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Fig. 3. Satellite maps for three studied central urban parks in Quito, Ecuador: c) La Carolina; f) El Ejido; and i) La Alameda. Spatial distribution of $PM_{2.5}$ concentrations in urban parks: b) La Carolina; e) El Ejido; and h) La Alameda; in the context of urban road infrastructure with typical rush hour traffic on the bordering roads (i.e., google traffic, ranging from light – green, moderate – yellow, red – slow, to dark red – very slow traffic)), panels c, f and i, respectively. Normalized Difference Vegetation Index (NDVI) for: a) La Carolina Park; d) El Ejido Park; and g) for El Ejido area. Human markers represent relative numbers of park users during daytime (the smaller or larger size of the markers represent lower or higher usability of the park area, respectively).

individuals engaged in physical exercises and experiencing an increased respiratory rate. With prolonged use of park peripheries, it could potentially evolve into a long-term exposure issue. Urban parks are frequently visited by residents, commuters and employees, making them attractive locations for restaurants facing the park. As the local climate permits, many food-related businesses lack doors and remain open to the streets, exposing their patrons to toxic pollution.

Unfortunately, addressing this problem is challenging sue to the entrenched use of poor-quality fossil fuel-powered public and private transportation that congests vial infrastructure in montane city centers, leading to elevated pollution levels. This study highlights an increased risk of health issues and economic losses that could be otherwise avoidable.

Additionally, our results suggest the need for more rigorous planning of urban park buffer zones. Similar to protected natural areas that require a buffer zone, urban parks demand meticulous planning to shield their users from harmful air pollution. A recent report from Hong Kong can help identify the best option (e.g., ranging in efficiency from a wall to different types of vegetation) to reduce the $PM_{2.5}$ levels in an urban park, depending on the distance from the road (Xing and Brimblecombe, 2020b). If creating buffer zone is not feasible, safety measures could be implemented by avoiding distribution of heavy diesel-powered traffic along the central park limits.

3.3. $PM_{2.5}$ correlation with Normalized Difference Vegetation Index (NDVI)

First, upon visual evaluation, both low NDVI and high $PM_{2.5}$ concentrations appear to coincide in most areas of the studied parks. It can be observed that in certain focal points, such as the intersections of main busy avenues, the relationship between the two variables is evident. Additionally, it is apparent that the areas inside the parks with forest vegetation (high NDVI) showed lower $PM_{2.5}$ concentrations.

However, when considering the ability of the NDVI model to predict $PM_{2.5}$ concentrations, Geographically Weighted Regression (GWR) showed that NDVI was able to predict the spatial concentrations of $PM_{2.5}$ with a low (i.e., La Carolina and El Ejido) and moderate (i.e., La Alameda) coefficients of determination (R^2) (Fig. 3a,b,d,e,g,h). Table 1 summarizes the goodness-of-fit information of the models. For the larger parks, La Carolina and El Ejido, low coefficients were obtained: $R^2 = 0.17$ and 0.15, respectively. Meanwhile, for the smallest out of the three studied parks, La Alameda Park, the model performed much better ($R^2 = 0.48$). These statistics are also represented in R^2 adjusted and the Residual Squares values. Squared residuals measure the difference between the actual $PM_{2.5}$ data and the predicted $PM_{2.5}$ values. When that difference (i.e., squared residual) is small, it means that the model performance is satisfactory, as is the case of La Alameda Park.

However, there is something specific with the other study areas preventing a good prediction of $PM_{2.5}$. Different factors might be at fault, such as size, or shape of the city park (e.g., square vs. elongated shape). Additionally, the infrastructure of the park, and prevalent winds could be considered (Xing et al., 2019; Xing and Brimblecombe, 2020a). For example, while the vegetation might be less complex (i.e., lower NDVI) further away from the main streets, the $PM_{2.5}$ concentrations will already be lower there as they have been filtered out by passing through the vegetation on the borders of the park. Also, some temporary pollution sources (e.g., ambulatory food vendors, smoking, flowering plants, etc.) might be present at a specific moment, but not the next, which won't reflect in the quality of the vegetation.

Table 1
Statistics for correlation analyses between the spatial distribution of $PM_{2.5}$ concentrations and NDVI index at three urban parks (i.e., La Carolina, La Alameda and El Ejido) in Quito, Ecuador.

Urban Park	R^2	R^2 Adjusted	Residual Squares	Samples
La Carolina	**0.17**	**0.16**	8.74	4998
La Alameda	**0.48**	**0.4**	5.71	431
El Ejido	**0.15**	**0.13**	30.79	697

Therefore, new elements must be included that can better characterize the vegetation or park infrastructure to be able to relate it to $PM_{2.5}$ levels more effectively. Specifically, elements related to the volume of vegetation or organic carbon absorption of each specific species or trees can be measured using another type of technology or sensor such as lidar, which is able to provide a more precise characterization of the vegetation. This could help highlight greater differences in the relationship between vegetation and concentrations of $PM_{2.5}$. However, what was achieved in this study is an effort to see how and if the NDVI - the vegetation's own indicator - marks a relationship with $PM_{2.5}$. The NDVI alone to predict air quality in any park is not enough; however, it produced promising results for one out of three city parks.

4. Conclusions

When examining montane cities, it becomes evident that their expansion tends to be constrained by changes in the surrounding terrain. The expanded hypercenters of Latin America continue to be attract the highest urban mobility resulting from urban sprawl and various anthropogenic activities (e.g., work, leisure, sports, etc.). This is particularly true in the case of Quito, Ecuador, where the urban hypercenter is situated in the narrowest (~3.5 km) part of the city and must accommodate all major avenues and highways necessary for the daily commute from the distant extremities of the >40 km long city. As a result, there is an extreme density of high-flow overcrowded roads and avenues, leading to large mobile emissions per area. Factors such as low-quality fossil fuels, a lack of proper motorized fleet maintenance, gradient-related breaking and acceleration, and hectic driving style contribute to increased atmospheric pollution.

After studying three central parks in Quito, it is evident that pollution levels along the park edges, near busy avenues, can reach hazardous instantaneous (10-s average) peak levels (1.1–2.4 mg m^{-3}), similar to being on a busy and highly polluted street. This is because all studied central parks in Quito are located near at least one overcrowded and polluted avenue. $PM_{2.5}$ concentrations decrease to healthier levels (1–22 μg m^{-3}) inside all the parks, consistent with existing scientific literature. However, most park visitors choose to walk or jog on the outside of the park due to personal safety concerns, given the country's increasing crime rates. This behavior raises concerns for both short- and long-term exposure to toxic exhaust from city traffic, especially for at-risk populations and individuals engaging in physical exercises with an increased respiratory rate.

Exposure to unsafe levels of air pollution is of a particular concern in Latin American cities due to lower standards of mobile technologies and fuel quality compared to the developed world. This issue is further aggravated in high elevation city Quito due to its connectivity issues, driving conditions and styles, and the lower oxygen effect on combustion efficiency. Additionally, our findings underscore the pressing need for improved urban planning, suchs as urban park buffer zones or, at the very least, avoiding the distribution of heavy diesel-powered traffic along the central park limits.

The Normalized Difference Vegetation Index was used to model the spatial concentrations of $PM_{2.5}$ in the investigated urban parks with a low to moderate coefficient of determination. For the smallest of the three studied parks, La Alameda Park, the model performance was promising ($R^2 = 0.48$); however further research is requires to optimize its overall performance.

CRediT authorship contribution statement

R. Zalakeviciute: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **S. Bonilla Bedoya:** Data curation, Formal analysis, Methodology, Software, Visualization, Writing – review & editing. **D. Mejia Coronel:** Data curation, Methodology, Software, Writing – review & editing. **M. Bastidas:** Investigation, Methodology, Software, Visualization. **A. Buenano:** Formal analysis, Investigation, Methodology, Software, Writing – review & editing. **A. Diaz-Marquez:** Conceptualization, Funding acquisition, Investigation, Visualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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