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Using Inverse Distance Weighting to Determine Spatial Distributions of Airborne Chemical Elements. Case Study: Douala, Cameroon

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ABSTRACT

Air pollution due to heavy metals has become a major problem in urban centers worldwide. Tree barks provide measurements of particulate concentration with an indication of the associated chemical composition. Assessing the air quality in a region is of paramount importance in ensuring the proper concentrations of particles in the environment, and their spatial location and distribution. Spatial modelling is a fundamental element in the tool chain for managing ambient air quality in a region. This study uses inverse distance weighting in the analysis of chemical elements from the barks of 254 trees to map heavy metals in the air of the city of Douala, Cameroon during the dry seasons (December to February, when monthly rainfall is low) of 2022. The ANCOVA model was used to compare metal concentrations in the bark with the dendrometric parameters of trees. The results may help in monitoring the spread of heavy metals in the city of Douala, in order to pinpoint the sites at risk. Our findings show that the whole city is in a state of emergency with respect to air quality, and mitigation measures must be taken rapidly throughout its territory, especially in intersections with high traffic volumes and industrial zones. We suggest planting several tall trees with large crown volumes and thick bark to reduce air pollution. Phenology and foliage appearance in trees can provide information on the type of metal-related pollution. These findings bring additional evidence that trees can act as bio-indicators and bio-accumulators in urban environments.

Keywords: Air pollution; chemical elements; spatial modelling; dendrometric parameters; bio-indicators

INTRODUCTION

Air Quality in Urban Environments

Air quality has received particular attention in recent decades due to the steady increase in air pollution worldwide, caused by the release of toxic elements into the atmosphere, mainly of anthropogenic origin. The majority of heavy metals, sulfur compounds and nitrogen compounds present in the atmosphere are considered to be pollutants originating from road traffic, industry, agricultural activities, etc. (Pitcairn et al. 1995, Whelpdale et al. 1997, Pacyna and Pacyna 2001). A high proportion of emitted compounds remain close to the source, but some can travel thousands of kilometers. Generally speaking, sulfur and nitrogen compounds diffuse into the atmosphere as gases, while heavy metals attach themselves to particles. Road traffic-related emissions of metallic particles can come from a number of sources, such as fuel and oil combustion, tire wear, exhaust pipes, lubricants, brake wear, corrosion of metal parts and resuspension of particles from the road surface (Thorpe and Harrison 2008, Karagulian et al. 2015, Pernigotti et al. 2016, Charron et al. 2019).

These traffic particles contain more traffic-related metallic elements (Pb, Cd, Cu, Zn, Br and Ni) than others (Lin et al. 2005). It has been identified that brake wear emissions contain significant quantities of Cu, Fe, Ba, Sb and Mn

(Monaci et al. 2000, Adachi and Tainosho 2004, Lough et al. 2005, Hjortenkrans et al. 2006, Iijima et al. 2007, Thorpe and Harrison 2008). On the other hand, certain metals, generally referred to as geogenic, such as Ca, K, Mg, Al, Fe and Mn, have also been identified as correlating with circulation markers (Monaci et al. 2000, Charron et al. 2019), while S is related to combustion and fossil fuel emissions (Liu et al. 2007, Hetem and Andrade 2016). In addition, Guttikunda and Kopakka (2014) revealed that an important increase in air pollution is to the result of the growth of the car fleet in urban areas. Epidemiological studies have revealed that these heavy metals can cause significant damage to the environment and ecosystems. Studies on the effects of air pollution on human health have shown that exposure to particulate matter can aggravate chronic respiratory or cardiovascular diseases, reduce immune defenses, damage lung tissue, lead to premature death, and possibly contribute to premature death and cancer (Bernard et al. 2001, Ibrahim et al. 2006, Alissa and Ferns 2011). Few studies related to the risks and impacts of air quality on human health have been carried out in Africa. For example, some studies report that residents of Nairobi, Sudan, Mali and Senegal are regularly exposed to high levels of fine particulate matter (PM) and are subject to serious long-term health risks (Kinney et al. 2011, De Longueville et al. 2013). Various heavy metals, such as Cu, Zn, Fe, S, Al and Ni, are known to be toxic and have adverse effects on human health, even over short periods of exposure (Fournier et al. 1988, Bernard et al. 2001, Ibrahim et al. 2006, Alissa and Ferns 2011). Characterizing the spatial variability of airborne pollutant concentrations and source apportionment is an issue of utmost importance for studies designed to quantify their adverse effects on human health and global warming (Zanobetti et al. 2009, de Brito et al. 2010, Santos et al. 2016). The environmental heterogeneity observed in urban areas, including the random distribution of traffic intensity (Janhäll 2015), requires spatial studies to understand and solve problems related to air pollution.

Theoretical Issues

Biomonitoring methods provide information on the quantity of pollutants and their effects on organisms that have been in contact with the pollutants. Plants are of great interest as biomonitoring tools. Their diversity offers a wide range of usable organisms: bryophytes, lichens, higher plants (herbaceous plants, leaves and bark of trees, etc.), used specifically or not to detect a large number of pollutants (e.g., ozone, nitrogen oxides, heavy metals, PAHs, dioxins, pesticides, etc.). Very few studies use trees as a bio-monitoring tool to visualize the distribution of heavy metals throughout a given region. A study in India investigated the spatial assessment of four heavy metals (Cd, Cr, Pb and As) in two mango (*Mangifera indica* L.*)* varieties (Dasheri and Langra) collected in the Saharapur district, using an inverse distance weighted (IDW) interpolation approach (Širić et al. 2022). However, very few studies have examined the distribution of sulfur, a major air pollutant that can harm animal and human health by causing bronchitis, bronchoconstriction and increased pulmonary resistance (Komarnisky et al. 2003, Weichenthal et al. 2021). The adverse effects of aluminum reported in recent years include Alzheimer's disease, dementia, hyperactivity and learning disabilities in children, yet very little research has been done (Cooke and Gould 1991). Knowledge on the spatial distribution of metals can help to formulate more rapidly the preventive measures aimed at reducing exposure to metals from the environment. Moreover, the tree fruit, although used as a basic tool to measure the different heavy metal concentrations in this study, is influenced by both climatic factors (temperature, rainfall) and factors specific to the plant (Paull and Janick 2008). It would not be very prudent to use it to understand the spatial distribution of heavy metals and compare species, as this implies waiting for the same period, which can vary according to the species and its variety.

A number of studies in this field have focused on the distribution of different pollutant emission sources via concentrations of chemical elements in tree bark (Ukpebor et al. 2010, Moreira et al. 2018), however, without examining the impact on air quality in sites close to and/or far from these emission sources, while other authors have chosen to assess the influence of trees' morphological properties on their ability to capture and retain pollutants. Chima and Opara (2019) revealed the influence of dendrometric parameters (total height, diameter at breast height, crown diameter, and basal area) on the absorption of gaseous pollutants, and particulate matter (PM).

Importance and Goals of the Study

So far, little attention has been paid to bark appearance and thickness, which seem to be important criteria for choosing the most absorbent species. Trees have been well-known for the usefulness of their bark in capturing metals in the air for a long time. Therefore, the discussion on bark selection criteria has become worthy studying. In this study, we decided to take into account its visible appearance and thickness and test its influence on the absorption of heavy metals. In addition, the physiological and morphological state of the tree after heavy metal accumulation has been neglected in many studies. The effects of heavy metals on plants include growth inhibition, structural damage and a decline in physiological and biochemical activities and plant function. Therefore, understanding the effects of heavy metals on plants and the mechanisms of resistance would enable plants to be used to clean up and remediate sites polluted by heavy metals (Cheng 2003). Hence the importance of paying particular attention to plants showing visible damage in this research through variables such as the aspect of foliage, ramification, bark smell, exudates, flowering and/or fruits. Some research has demonstrated the use of lichens, bryophytes and other epiphytes as bio-indicators of air pollution (Conti and Cecchetti 2001). These will be needed to validate the rising concentration of metals in the environment. In order to fill this gap, this article proposes a new method for measuring air quality across an entire territory, taking into account the spatial aspect of different sites. By combining in the analysis new variables rarely used before, it also provides new information on the use of higher plants as bio-monitoring tools for urban air quality.

Moreover, in Douala, a study aimed at characterizing the spatial variability of airborne pollutant concentrations and distribution of sources is necessary for monitoring air quality in the city. Considering the debates in the scientific literature related to the definition of the bio-monitoring method for urban air quality, this article focuses on the use of tree barks in higher plants as a process of change hindering the sustainable development of cities and metropolitan areas. Although useful for selecting appropriate species for mitigating pollutants in the air, the approaches developed on the concentrations derived from these tree barks to date explain neither the distribution of pollutants in a site taking into account the spatial aspect of neighboring sites, nor the extent of ecological effects on trees when absorbing heavy metals.

This study aims to visualize the distribution of heavy metal concentrations (Cu, Zn, Fe, S, Al and Ni) in the city of Douala. Taking into account the lack of measurement devices, which are generally rare in developing countries, the aim of this study is to predict the spatial distribution of pollutants over the entire area of the city of Douala via the concentrations of chemical elements in tree barks that discriminate traffic-generated air pollution using the IDW method. In this way, the amount of bark suitable for analysis can be taken without altering the tree's physiology. In particular, we focused our attention on Al, Fe, and Cu, which are related to re-suspension of road dust, on Ni, Cu and Zn, which are related to brake and tire wear, as well as on S, which is related to combustion and fossil fuel emissions, as reported in Liu et al. (2007), Hays et al. (2011), de Almeida Albuquerque et al. (2012), and Hetem and Andrade (2016). These specific emission sources are likely to be observed in Douala. We considered the tree species that are widely distributed in Douala to quantify their ability to record the fine spatial variability of air pollution. With the constraints on data availability for certain species on major roads in the city due to a delayed green infrastructure planning scheme, all tree species were considered to have the same pollutant absorption capacity. We believe that our method opens up new avenues for research, including the possibility of in-depth comparative studies at the national or international level.

The results of this study will contribute to the use of tree bark as a biomonitoring tool in urban landscapes to address the climate emergency.

MATERIALS AND METHODS

Study Site

Douala is the economic capital of Cameroon and one of its largest cities, with a population of over 3 million (Nana et al. 2014). The project was carried out in Douala, the Wouri department, Littoral-Cameroon region. Covering an area of approximately 923 km^2, this department is located between 3°40' and 4°11' north latitude and between 9°16'' and 09°52'' east longitude, at an altitude of 13 m. The area is subdivided into six territorially decentralized communities, namely the 1st, 2nd, 3rd, 4th, 5th and 6th district communities of Douala. The project was carried out in all these municipality districts, excluding Douala 6th (Manoka). As linear features, transects crossed several districts in each municipality. Douala is located at the foot of active volcano Mount Cameroon, with several summits having an altitude of 4100 m (Lenouo et al. 2009). According to Lenouo et al. (2009), such topography contributes to accelerating horizontal winds, up to about 7 m.s^{-1} near ground level.

Figure 1 shows the location of the case study area within the City of Douala, Cameroon.

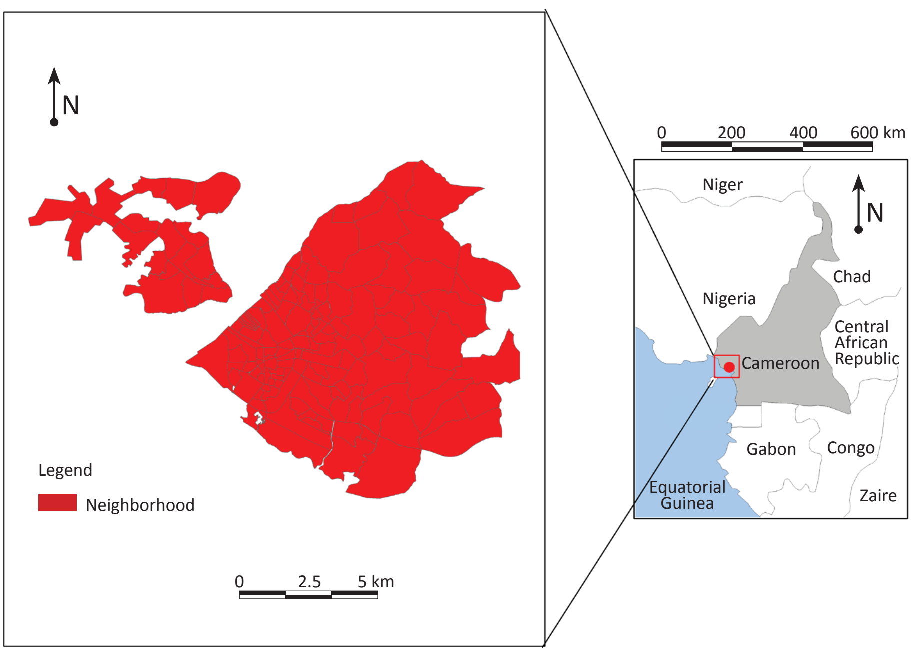

Figure 1. Position of the study site within the city of Douala, Cameroon, in a global context. The city of Douala is presented as a red circle in the right image, and the neighborhoods considered in our study are presented in the left image.

The tree study was conducted on the roads of the city of Douala, which has a climate belonging to the equatorial domain of a particular type known as "Cameroonian" (Din et al., 2002). This climate is characterized by two seasons with a long rainy season (at least 9 months), abundant rainfall (about 4000 mm per year), high temperatures (26.7°C) and stable weather conditions. Mean daily temperatures drop by about 2°C-3°C. The average minimum temperature in Douala is 22.6°C in July and the average maximum temperature is 32.3°C in February (Enete et al. 2014). Relative humidity remains high throughout the year and is close to 100% (Din et al., 2008). The city of Douala is full of many ecosystems of various types of nature (micro-ecosystems), each of which includes species adapted to the environment.

Data Collection

Tree bark samples of the selected species were collected in the city of Douala. Street trees and trees growing in rural areas were sampled near the streets with different traffic intensities. Only trees located no more than 5 m from the motorways were sampled. We selected individuals of similar size for each species, with a diameter at breast height of around 30 cm, from which we collected 5 × 5 cm bark samples. Dendrometric parameters were measured during the dry seasons (December to February, when monthly rainfall is low) of 2022. The height and crown height of the trees were measured using a height indicator. The canopy diameter was measured from horizontal and perpendicular directions of the street. The circumference of the tree trunk was measured with a tape measure and its diameter was computed by dividing the tree circumference by 3.142. The crown shape was related to standard shape constants and its volume was computed (Troxel et al. 2013) Flowering and fruiting were observed on each tree, as well as the presence of lichens. Foliage and bark appearance, bark cracks, ramification and exudates were observed during the study period. The geographical coordinates of each tree were taken using a smartphone with the application "Google Earth". The selected tree species were common to the geographic study area.

The average daily annual traffic intensity, which measures the number of vehicles passing through a section during the year, divided by 365, combined with the peak hour traffic intensity, which computes the number of vehicles passing through a section for one hour (the same time), were used to measure and categorize the traffic intensity. The roads of the city of Douala were group in three categories, with different traffic intensity:

- The first category of roads was the high traffic intensity, which groups the National Road No. 3 (the major road linking Douala, the economic capital, to Yaoundé, the politic capital), Aviation Highway, Japoma Road, Yassa Road, PK12 Road and PK14 Road (those roads leading to the outskirts of the city which are roads that bear the name of the place where they end) and boulevards (the roads inside the city centers, linking commercial and administrative centers),
- The second category of roads was the medium traffic intensity which groups streets (roads linking the neighborhoods to boulevards), avenues (larger than streets and generally having the characteristic of being lined with trees),
- The third category of roads was the low traffic intensity: generally unpaved and local alleys, roads within neighborhoods where traffic intensity is almost non-existent compared to others.

Sampling and Bark Preparation

Sampling was carried out during the dry seasons (December to February, when monthly rainfall is low) to avoid rain washing and fungal degradation of samples. All bark was collected with titanium tools to avoid contamination. From each selected tree, a 5 × 5 cm portion of the periderm was collected from each quadrant of the trunk based on cardinal points located 1.5 to 2.0 m above the topsoil, and these portions were pooled for analysis. The samples were then placed in paper bags and stored in a cabinet under low-humidity conditions until analysis could be carried out. Information concerning the geographical coordinates of the trees was also recorded. The collected tree barks were first cleaned with a soft cloth and a nylon dental brush to remove external materials such as dead insects, dust and lichen. Samples were obtained by rasping the outermost 3 mm of bark with a titanium tool (Wolterbeek and Bode 1995). Each sample was then ground to a powder.

Elemental Analysis

The bark samples were analyzed by the Research Institute for Analytical Instrumentation INCDO INOE in Romania using a portable X-ray fluorescence instrument (Bruker Tracer 5i). This technique was chosen due to its multi-element capability, sensitivity, easy sample preparation without sample digestion, accuracy of the results and analysis cost. The concentrations of Al, Fe, Zn, Cu, Ni and S were recorded for having well-described sources in Douala. These elements may be considered as proxies of the complex mixture generated by vehicular emissions. Although other elements were also measured by the XRF, their values were close to the limits of detection. Samples were measured using the calibrated method for soil supplied by the manufacturer. The acquisition time for each sample was 60 seconds (2x30 seconds acquisitions, using specific conditions for low-Z and respectively high-Z elements) and the samples were measured in normal atmospheric conditions.

The 25% threshold was applied to the uncertainly value in respect to the concentration value of Al, Fe, Zn, S, while 80% threshold was applied for Cu and Ni.

IDW Interpolation

The inverse distance weighted (IDW) method is used to interpolate spatial data based on the concept of distance weighting. This method can be used to estimate unknown values of pollutants from the known (adjacent) measured values of pollutants with specifying search distance.

The IDW formulas are given in Equation 1:

$$\frac{\sum_{i=1}^{n} h_i / d_i^2}{\sum_{i=1}^{n} \left[1 / d_i^2 \right]} \tag{1}$$

Where *Hp* is the computed pollutant concentration value of point *p* in which the interpolation is performed (ppm); *hi* is the measured value used to compute the estimated value at point *p* (ppm); *di* is the distance of the points from point *p*; *n* is the number of points used in the interpolation procedure for estimating the value of point *p*.

Statistical Analysis

Pollutant mapping was carried out using ArcGIS version 10 with spatial analysis extensions. The association between element concentration in bark and dendrometric parameters (measured by crown volume, tree size, bark thickness, foliage appearance, and diameter at breast height and fruit presence) was assessed by using the Analysis of Covariance (ANCOVA) (Kutner et al. 2005), a method used to look at the simultaneous influence of qualitative and quantitative predictors on a variable of interest. EpiData version 3.1 software was used for creating the data form and the data entry, EpiData Analysis version 2.2 for the transformation of variables and descriptive analysis. The R version 4.1 software was used for the ANCOVA.

RESULTS

Distribution of Iron (Fe) Content Sampled on Tree Bark

Figure 2 shows the spatial distribution of 254 points surveyed in the study area. The higher concentrations, depicted using larger and darker circles, seem to be located towards the edges of the study area.

Statistical Description of Heavy Metal Parameters in Bark

Table 1 shows the statistical distribution of data on the concentration of heavy metals from the study area.

The analysis of metal concentrations shows that there is little variability for heavy metals Al, Ni and Cu contained in tree bark, indicated by a low coefficient of variation (< 50%). However, there is considerable variability for metals such as Fe and Zn. These data show an asymmetrical distribution.

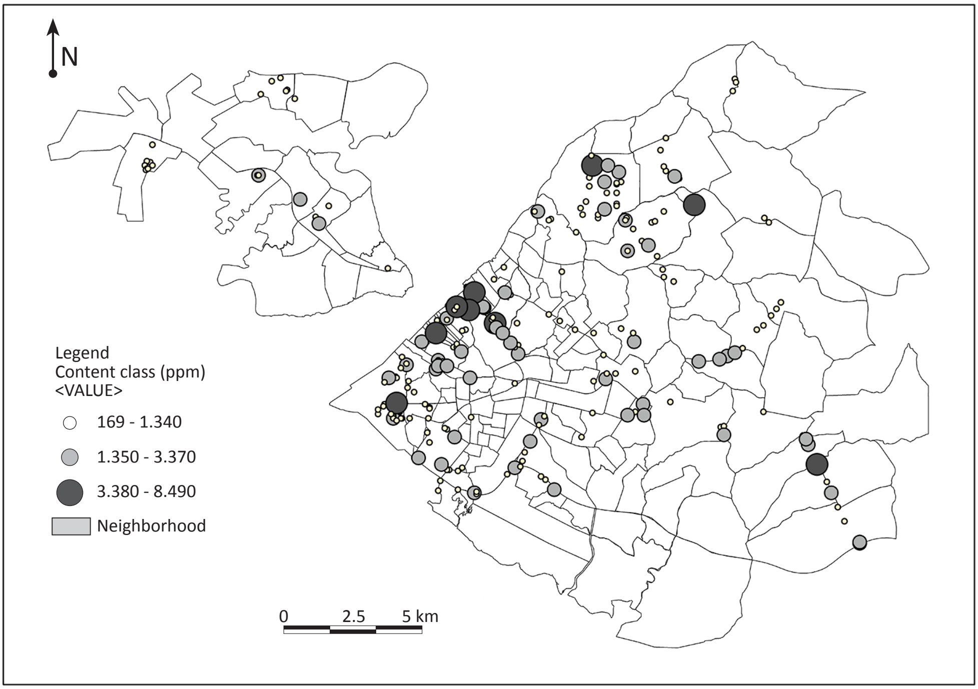

Figure 2. Spatial distribution of survey points. The higher concentrations are depicted using larger and darker circles.

Table 1. Statistical parameters for the concentration of heavy metals in Douala, Cameroon.

Parameter	Min	Max	Mean	Standard deviation	Coefficient of variation (%)
Al (ppm)	53,477	110,936	78,046.00	13,526.68	17.33
S (ppm)	275	18,557	2,975.00	3,431.63	115.36
Fe (ppm)	169	8,491	1,133.40	1,077.85	95.11
Ni (ppm)	8	36	13.49	3.87	28.68
Cu (ppm)	8	42	17.22	6.98	40.55
Zn (ppm)	10	529	55.62	51.40	92.42

Heavy Metals by Similarity Group

Heavy metals were divided into 3 classes according to their distribution in the study area: the first group included Al and Ni, the second Cu, Zn and Fe, and the third S (Figure 3).

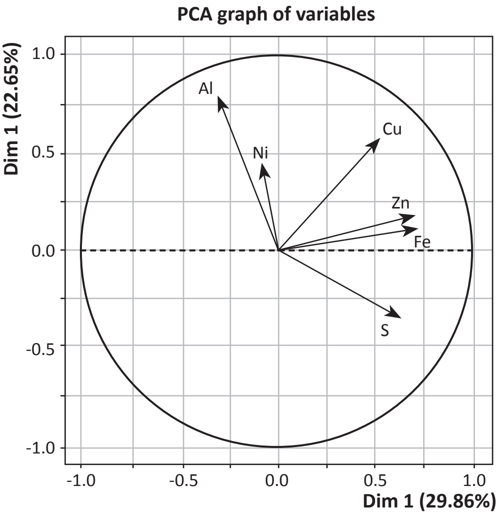

Figure 3. Grouping of heavy metals in Douala, Cameroon by their spatial distribution.

Spatial Prediction of Heavy Metals in the Study Area

Figure 4 shows the results obtained from the spatial prediction of heavy metals using the IDW method**.**

We noticed an irregular spatial distribution of heavy metals in the different areas within our study region. They are more concentrated in the western, eastern and central parts of the large study area than in other parts. There is a multitude of sites with high Al concentrations in the central part of our study area, with closer neighbors having low concentrations. This spatial distribution is almost identical to that of nickel (Ni), as they belong to the same chemical group. The spatial distribution of Fe shows rather homogeneous zones with close neighbors, and a high concentration in the central part and at the western and eastern extremities. The same is true for heavy metals in the same chemical group, such as Cu and Zn. Areas closer to highly polluted sites are more affected than those further away. There are very few low-concentration sites in the study area. The spatial distribution is similar to that for Fe, the only difference being that it seems to be more concentrated in the extreme parts of the study area than in the central part.

However, it should be noted that these different heavy metals are present in the same polluted sites, and the degree of pollution varies from one site to another depending on the heavy metal.

Factors Influencing Heavy Metal Storage in Tree Bark

The ANCOVA revealed that street classification, bark thickness and canopy volume have a significant influence on

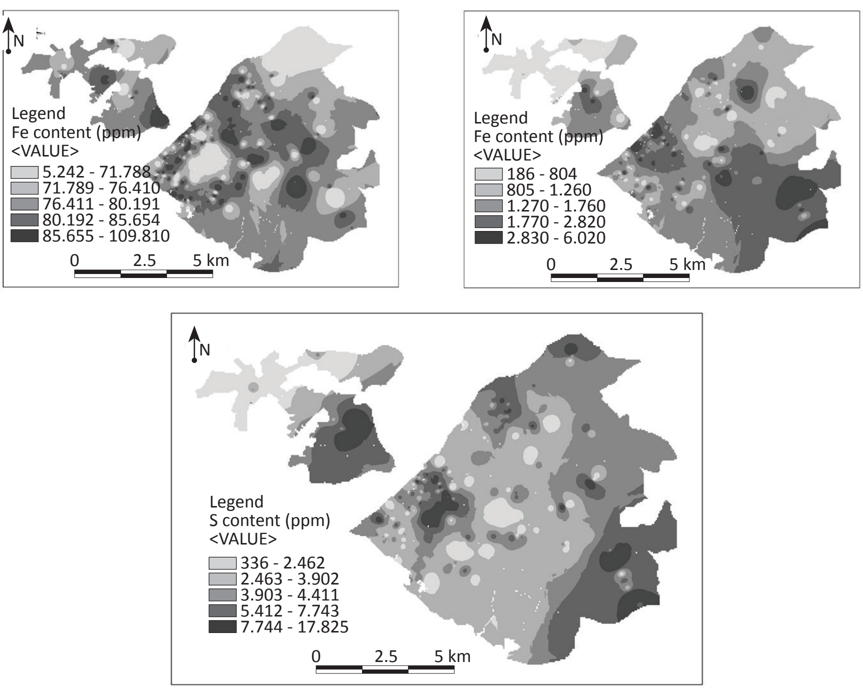

Figure 4. Spatial distributions of heavy metal concentrations: **(a)** Aluminum (Al); **(b)** Iron (Fe); **(c)** Sulfur (S).

the storage of heaviest metal in tree bark. Al storage by trees is conditioned more by the appearance of the bark than by its thickness. Tree size also influences Zn storage (P-value ≤ 0.1). In return, these heavy metals influence the morphological and physiological characteristics of the plants. Almost all heavy metals increased the nauseating effect of bark and played a role in the flowering and production cycle of the trees. Foliage was affected by the presence of metals such as S and Zn in their bark. Each concentration means prediction based on the ANCOVA models shows that the quantity of exudates decreases in plants with sulfur concentration. The absence of lichens on the bark is due to the high concentration of S and Zn in the bark. Their toxicity leads to irreversible branching in the plant. The accumulation of Ni in the bark of the plant seems to favor the appearance of certain epiphytes different from lichens (Table 2).

DISCUSSION

Overall Significance and Meaning of Results

A total of 254 points were inventoried, covering most of the study area. This reflects the public authorities' desire to make the city green and resilient by planting trees along roadsides. Some roads on the outskirts of the study area were devoid of trees, as they were mainly occupied by households, with citizens deciding to raise buildings to the detriment of plants in order to make profit. The distribution of heavy metal concentrations showed that the points with the highest air pollution were closer to the source of pollution, which could be industry, households or vehicles. According to the development plan for the city of Douala until 2025, there were around 2,886,000 inhabitants and a fleet of over 1,231,607 vehicles, most of which are ageing (Douala Urban City Council 2015, unpublished data) corresponding to almost 1 car for every 2 inhabitants. Douala's citizens and vegetation are, as in most developing countries, exposed to a high, and geographically variable, concentration of $PM_{2.5}$, generated mainly by vehicle traffic. According to a World Bank report (2004), Douala's transport sector has the highest fuel consumption (62%), followed by industry (28%) and households (10%). In addition, Hoban and Tsunokawa (1997) showed that gas emissions from vehicles depend on fuel type, age, speed and level of vehicle maintenance. Much of the increase in air pollution is attributed to the growth of the vehicle number (Guttikunda and Kopakka 2014). Douala, a coastal city with many narrow streets, is growing rapidly due to the rural exodus. Motorcycles account for the majority of traffic (Sahabana 2006, Sakai 2020). The study area is an industrial city with numerous cement, food, refinery, gas, cosmetics and other industries. Illegal sales of adulterated fuels are common along the city's roads. This considerably increases the concentration of pollutants in the environment. Heavy metals can travel dozens of kilometers affecting the health of citizens and vegetation near or far from their source of emission (Adiang et al. 2017).

The results of our sample analyses bring additional evidence for the presence of heavy metals in tree bark. The results show that the study area may be facing a health crisis due to the accumulation of these particles in the air. Limit values for copper (Cu) and zinc (Zn) are set at 100 mg/kg or 100 ppm. The results show that the average values found are within the limit ruling out any danger to users. Nevertheless, there were some samples with zinc values in excess of the standard, ranging from 100-529 ppm at certain sites in the study area. This metal, Zn, can cause irritation of the mucous membranes, gastrointestinal and skin irritation, fatigue and shivering (Botella et al. 2011, Okewale and Grobler 2023, Mahmood 2023). It is important to define these risk zones and take mitigation measures to further reduce these metals. The normal value for nickel (Ni) is set in the range 1-50 mg/kg or 1-50 ppm. The average values found in the results are within the limit, but some samples showed values very close to the limit in the sites. These values should draw attention to take preventive measures against this metal. However, the levels of Zn and many other heavy metals exceeded the threshold value in some samples located close to the emission source at different sites. Particular attention should be paid to the location of

Table 2. Factors influencing the concentration of heavy metals and the characteristics of barks determined by heavy metals.

Parameters		Al	S	Fe	Ni	Cu	Zn
Factors influencing heavy metal absorption	Tree size						<.001
	Aspect bark	0.023					
	Bark thickness		0.010	0.080		<.001	
	Crown volume	<.001		0.001	0.021		
	Street classification	<.001	<.001	<.001	<.001	<.001	<.001
Effects of heavy metals on plants	Bark smell	0.069		0.063	0.002		<.001
	Exudates		0.007				
	Aspect foliage		0.028				0.003
	Lichens		<.001				<.001
	Other epiphytes				0.006		
	Ramification		0.016				0.082
	Flowering and/or fruits	0.053	<.001			0.056	0.043

polluted areas in order to maximize mitigation measures in these locations compared to other sites.

The heavy metal pollution map identified most at-risk sites in the study area. Most of the maps show the western, eastern and central parts of the large study area as emergency sites, where mitigation measures should be rapidly taken to ensure the health of population, compared with other parts. This is the case for the majority of heavy metals. The western and eastern parts are the study area's only gateways to and from other cities in the country. The western part also includes the city center, where the majority of the city's activities take place. Almost all users converge on this area every day, using vehicles for administrative and/or commercial purposes. Vehicles leaving or entering the city on the west side meet up with those going into the city center, creating traffic jams at the 'Rond-point Deido', passing through the commercial zone (Akwa) to the administrative zone (Bonanjo). During the hours of traffic jams, the concentration of pollutants in the environment increases with the age of the vehicles, most of which are over 12 years old (Adiang et al. 2017). The entire commercial zone is besieged by pollution that can reach nearby sites. The use of adulterated fuels increases gas emissions from vehicles into the environment with driving speed (Hoban and Tsunokawa 1997). This explains the high concentration of metals in the western part of the large study area. There are very few roads leading to the city center, which explains the traffic jams at certain crossroads in the city between 06:00 and 08:00 in the morning, the time when people go to work, and between 17:00 and 19:00 in the evening, the time when people return home. Metal concentrations are very high at these locations in the central part of the study area. These include the Ndokoti-pk8-logbaba crossroads with the nearby industrial zone, the Nyalla crossroads, Bependa, Makepe-Logpom etc. Heavy metals are easily dispersed around these crossroads, affecting nearby sites. The eastern part of the study area is also a communication route with Yaoundé, the national capital. Much coveted by users and vehicles alike, this eastern part contains a large crossroads called 'Carrefour Yassa', which has become a commercial hub for many. It is also an area full of industry and always jammed with traffic. The pollution map shows this part as an area at risk, where mitigation measures should be taken quickly. The small part of the study area, dislocated from the larger region by the Wouri River, is an integral part of the city. It is also home to industries, and the narrowness of the roads makes traffic jams easy. This increases the concentration of metals in the air. Indeed, during periods of congestion, due to poor vehicle maintenance, brake wear increases the production and release of heavy metals such as Fe and many others (Harrison et al. 2003, Bukowiecki et al. 2010, Hays et al. 2011) in the environment. Ni is generated from the combustion of lubricating oils and stainless steel (Dall'Osto et al. 2012). Al is generated from multiple sources, including resuspended road dust (Lee et al. 1994).

Several studies suggest that local air pollution is reduced by the presence of trees (Vailshery et al. 2013, Nowak et al. 2014, Janhäll 2015, Jeanjean et al. 2016). Several factors are involved in the filtering and dispersion of air pollution by the presence of trees (Selmi et al. 2016). The main interaction is dry deposition, which is the mechanism by which vegetation removes atmospheric pollutants in the troposphere during periods of non-precipitation. It depends on the combination of pollutants (e.g. gas/particles), surfaces (e.g. size, roughness, chemical nature) and microclimate (e.g. wind speed and direction, temperature, solar radiation, air turbulence) (Selmi et al. 2016). The ANCOVA shows that the type of species is crucial in reducing air pollution, since different species present different bark morphologies that can potentially influence the absorption of metals present in the air. Size, bark thickness and crown volume are the parameters with the greatest influence on the reduction of the majority of metals in the environment. The greater the size, the greater is the plant's capacity to eliminate Zn and many other elements from the air. Most of these metals in PM_{10} are able to reach a certain height before triggering chemical reactions with other compounds present in the air, which can arrive dozens of kilometers from the source of emission. It is important to plant large trees with a good crown volume and maximum bark thickness to significantly reduce airborne heavy metals. The appearance of the bark (roughness) is crucial for the absorption of Al in the environment. In fact, Al belongs to dusts made up of solid particles smaller than 75 µm, the larger ones falling close to the source of the emission. The rough bark easily traps these particles and eliminates them into the air. This corroborates with the work by Selmi et al. (2016), who showed that the reduction of pollutants in the air by trees depends on the combination of pollutants (e.g., gaseous/particulate), surfaces (e.g., size, roughness or chemical nature) and microclimate (e.g., wind speed and direction, temperature, solar radiation, or air turbulence).

However, heavy metals accumulate in living organisms and disrupt biological equilibrium and mechanisms. Metallic particles of atmospheric origin can act in different ways on trees: they can cause abrasions, reduce photosynthesis, cause injury to leaves or integrate through the cuticle (Grantz et al. 2003). Accumulation of heavy metals in trees delays the flowering cycle in our study. In fact, the increased number of these particles in the air will settle on the surface of plants, thus reducing photosynthesis and delaying plant phenology, and leading to a drop in fruit yield, and in some plants, even to its absence. Dust absorbs and scatters light, limiting visibility. It can also form dirt that has an unpleasant odor. The yellowing of leaves and defoliation of trees is due to the presence of heavy metals such as S and Zn in their bark. In addition, the secretion of exudates by trees is reduced with the increase of content of heavy metals. Excessive accumulation of these metals changes the plant's metabolism and conditions the presence of epiphytic lichens and mosses on the tree trunk.

Scientific Significance and Importance of Results

The absence of air quality monitoring plans despite the number of ageing vehicles and the consumption of adulterated fuels of national and local importance determined the need to develop an innovative study for the design of the mapping of sites at risk in the Douala metropolitan area. This study approaches and recombines natural resources in new and creative ways, in order to control the environmental challenges facing Douala.

Overall, our study makes a significant contribution to characterizing the spatial variability of airborne pollutant concentrations and source apportionment, providing tools for mapping the spatial distribution of pollutants in major cities and their metropolitan areas. Implicitly, our methodology contributes to improving air quality and mitigating environmental threats due to climate change, thereby contributing to urban sustainability.

Two main elements contributed to the production of the heavy metal pollution map in the Douala metropolitan area: the GIS tools IDW interpolation method, which is based on the concept of distance weighting, and heavy metal contents measured on bark taken from trees near roads at different road traffic intensities. Using these methods, spatial analyses between sites were carried out, and values were predicted even in unsampled sites. High-risk sites were identified with some accuracy.

The methodology used in this study offers the advantage of a simple, precise technical solution compared with other international studies (Ung et al. 2001, Maignant 2006, Doumbia et al. 2021). The chosen technical solution requires high quality data and experience in GIS processing and implementation. The use of data taken from tree samples at different road traffic intensities and application with GIS tools is another advantage of the methodology for identifying at-risk areas in the city and the behavior of its neighboring areas in order to monitor air quality in the city. The study demonstrated the need to integrate air pollution mitigation goals and related objectives into the green infrastructure planning strategy targeted by political authorities.

Methodological Limitations and Future Research Directions

The study's limitation is the lack of data collected in certain districts in the north-east and south-east of the city, due to the absence of trees in these areas. In addition, Douala is a city with a precarious architecture in terms of green infrastructure. The authorities' desire to make the city green and resilient was motivated not so long ago, hence the presence of shrubs in some parts of the city, with very young bark that could not be used for further research. The urban trees were mainly located in the city center, and for the most part date back to colonial times. At some sites, their presence was conditional on the will of the population, which often made it difficult to collect data on them. Even if IDW interpolation method solves the problem of lack of data at unsampled sites, a future quantitative and qualitative assessment of tree bark must be carried out at unsampled sites, extending the radius of collection to reach trees far from traffic, with the participation of all stakeholders. This will enable us to compare these data with those predicted by spatial interpolation. Prediction by IDW interpolation method is more accurate when data size increases and when it is representative of the study environment.

Future research should focus on the planning of green infrastructure in the city, with emphasis on polluted and high-risk areas. This could be achieved by designing ecological corridors along the roads of polluted sites and creating parks not far from these sites to purify the air throughout the area. The choice of tree species will be important in improving air quality. The identification of tree species with a better capacity to record the fine spatial variability of air pollution is still little known and constitutes an important research topic. Bark morphology is subject to a high degree of interspecific variability (Yunus et al. 1990, Junikka 1994) that can potentially influence the species' ability to record airborne element concentrations (Szczepaniak and Biziuk 2003). This is particularly important because some species may be better suited to the role of biomonitoring than others (Moreira et al. 2018).

CONCLUSIONS

This article proposes a new method for assessing air quality in complex urban environments, with an explosion of the number of motorcycle cabs and a vehicle fleet consisting mainly of second-hand vehicles. Accessing the variability of air pollution therefore requires a dense network of measuring devices, which are generally scarce in such environments. Mapping the chemical composition associated with road traffic particles in the city of Douala required heavy metal contents from tree samples collected near roads at different traffic intensities and the GIS tools IDW interpolation method which is based on the concept of distance weighting.

An important operation in our methodology was to predict the value of heavy metal contents in unsampled areas to monitor their propagation in the environment. The results proved that tree bark is a reliable measuring instrument, useful for assessing the fine spatial distribution of chemical element concentration that increases with traffic intensity. The heavy metal content was relatively high in locations close to the emission source. The whole city of Douala is in a state of emergency with respect to air quality, and mitigation measures must be taken rapidly throughout its territory, especially in intersections with high traffic volumes and industrial zones.

The quantitative approach presented in this article could benefit from more in-depth analyses to identify hotspots in highly urbanized areas. These analyses will enable researchers to delimit with a high degree of precision the sites that need to be closely monitored. The results of this study can help planners to propose appropriate strategies for the creation of urban parks near heavily polluted sites, and establish ecological corridors along these routes to improve the quality of life in the surrounding environments. Our study suggests using large trees with bark thickness and crown volume large enough to reduce heavy metals generated mainly by road traffic. Phenology and foliage appearance in trees can provide information on the type of metal-related pollution in the study area. Consequently, trees can act as bio-indicators and bio-accumulators in urban environments.

To summarize, the principles for implementing green solutions must be compatible with the general principles of spatial planning and environmental protection. The most difficult problem in defining and managing green infrastructure for metropolitan areas in large cities is data collection and quality assessment.

Author Contributions

JMFM, ANY, JRP and A-IP conceived the study. JMFM sampled the trees; JMFM and CT analyzed the chemical composition of the barks. JMFM and A-IP analyzed the data. JMFM, CT, ANY, JRP MK and A-IP interpreted the analysis results and wrote the manuscript.

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Conflicts of Interest

The authors reported no conflicts of interest.

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