Air Quality and Its Relationship with the Community Birds from the Sierra de Guadalupe, México

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Abstract. The air quality in Mexico City (CDMX) is currently evaluated by the Air and Health Index (AHI), which does not consider the joint effect of the mixed pollutants, neither the damage to biodiversity. The development of an index that evaluates these effects and the use of atmospheric dispersion and trajectory models such as the Hybrid Single-Particle Lagrangian Integrated Trajectory Model (HYSPLIT) supports the design of an Integrated Air Quality Index (IAQI). This study aimed to evaluate the relationship between bird diversity and air quality, based on a pollutant analysis and the IAQI at the Sierra de Guadalupe, CDMX, Mexico (SG-CDMX). A bird census was conducted at SG-CDMX (Jan-Feb 2020). The values of structural and functional diversity of communities and AHI of CO, O_3, Particulate Matter (PM) $PM_{2.5}$, and PM_{10} were obtained. The relationship between bird diversity and the IAQI proposed was assessed with a Principal Component Analysis. The HYSPLIT model was computed using satellite images. Heat maps of AHI and weather parameters were developed with QGIS. Southern sector sites reached the highest IAQI and AHI values, which were associated with the higher vehicular influx and industrial activity (IAQI increased when air quality was lower). While the northern sites presented the highest values of structural diversity and air quality, these sites have conservation land use and lower anthropogenic activity. Furthermore, the HYSPLIT model shows that the trajectories and movement of particles are from southwest to northeast.

Keywords: Air Quality · Integrated Air Quality Index · Birds · HYSPLIT model · Sierra de Guadalupe

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1 Introduction

Mexico City has had several air pollution-related problems for more than 40 years. These problems are mainly due to the intense burning of fossil fuels, generated mainly by mobile (motor vehicles) and fixed (industry) sources, resulting in high levels of air pollution [1]. Sierra de Guadalupe Protected Natural Area is located in the north of Mexico City and the south of the State of Mexico, near to the Vallejo Industrial Area, in Gustavo A. Madero and Azcapotzalco mayors, and the industrial zone of the Tultitlán and Tlalnepantla municipalities [2]. This area is highly influenced by vehicular traffic and industrial emissions. It is known that the wind direction in Mexico City generally goes from the north to the south, which causes the pollutants of the area to be dragged towards the central and southern areas of Mexico City [3]. Thus, the northern part of the CDMX has become a place of great importance for the study and evaluation of air quality.

Associated with high levels of air pollution, various damages to human health have been observed and studied, which have been found mainly in the respiratory, circulatory, and cardiac systems [4]. However, damage to wildlife and ecosystems has also been observed, such as birds, which have exhibited damage at different levels of biological organization, from cellular to population [5, 6]. Birds have also been used as air quality bioindicators and as biological condition indicators of various ecosystems [7, 8].

Due to the high air pollution episodes in the Metropolitan Zone of the Valley of Mexico (MZVM), in 1982 the Metropolitan Index of Air Quality (IMECA) was developed, widely disseminated in 2006 [9]. However, since February 18, 2020, the Air Quality and Health Risk Index "Air and Health Index" (AHI) came into force, which was incorporated by the Official Mexican Standard NOM-172-SEMARNAT-2019, leaving IMECA deprecated. Both indexes address the different risks of each pollutant criteria in human health and established risk categories for the different sectors of the population. None of these takes into account the risk to human health from the mixture of all criteria pollutants since they are only assessed for each pollutant separately [10]. On the other hand, these indexes only refer to risks to human health and do not cover the risks or damage that may arise in biodiversity and ecosystems.

For this reason, it is important to develop an index to assess the damage exerted by the mixture of various pollutants to human health, biodiversity, and ecosystems. Likewise, the use of tools such as the Hybrid Single-Particle Lagrangian Integrated Trajectory Model (HYSPLIT) and the elaboration of heat maps with QGIS, allow us knowing where the atmospheric pollutants moves and its possible affectations [11]. Thus, they are also very useful in the development and interpretation of an Integrated Air Quality Index, as well as in any assessment of air quality.

2 Background and State-of-the-Art

2.1 Air Quality

In Mexico, since the 1950s, some air quality studies were already carried out, which considered some effects of air quality on human health. While, in the 1960s four atmospheric monitoring stations were installed to assess the air quality of the Metropolitan

Zone of the Valley of Mexico and in 1973 there were already 14, incorporating them into the United Nations Program [9]. Currently, there is the Atmospheric Monitoring System which has 45 monitoring stations located at different mayoralties of the CDMX and at some municipalities of the State of Mexico [12].

Since February 2020 the Air and Health Index is calculated, which is reported every hour on the website www.aire.cdmx.gob.mx, informing the population about the current air quality condition. This index entered into force due to the publication of NOM-172-SEMARNAT-2019. Also, this Air and Health Index displaced the Metropolitan Air Quality Index (IMECA), which was designed in 1982 and entered into force in 2006 [10].

In recent years, several authors have conducted various air quality assessments in Mexico City and other Mexican metropolitan areas. They have used the data obtained from different monitoring stations of the Metropolitan Zone of the Valley of Mexico. They have proposed various methods of information analysis, such as sorting models (Principal Component Analysis) [13]. They have also assessed the pollution levels at different times of the year [14] and have used satellites for monitoring urban CO emissions [15].

2.2 Birds as Bioindicators

Birds are considered good environmental and air quality indicators [16]; thus, several researchers have used them as indicators in various regions of the world. These researchers found a relationship between the high species diversity with green urban areas; as well as, associated with a good quality of life [17, 18]. Similarly, a relationship has been found between various damages from the individual level (in different organs and tissues), population level (reproductive), and community level, with the constant exposure to atmospheric pollutants [5, 6].

On the other hand, birds have been used to assess the biological condition of various ecosystems. Regional assessments of forests and the impact of different land uses have been carried out, through the relationship between functional diversity, structural diversity and environmental parameters that has a remarkable relationship with alterations in the ecosystem [7, 8, 19]. These studies have enabled researchers to detect early warning signals of the current condition of ecosystems and alert decision-makers implementing appropriate measures to protect and prevent ecosystem degradation.

To know the bird community, is important assessing the structural diversity (the diversity of organisms in the community) through the Simpson Index, Shannon Index, and Maximum Diversity. As well as which species are dominant or what is the evenness of the ecosystem [20]. Functional diversity is obtained to understand the relationship between structural diversity, community, and ecosystem functioning. In the case of birds, functional diversity can be known through food guilds, food substrate, habitat preference, and nesting mode, among other traits of birdlife or ecological histories, and the different environmental parameters assessed [8].

3 Objective

This work aimed to evaluate the relationship between the structural diversity scores form the Sierra de Guadalupe bird community and the air quality in the area, by analyzing air pollutants, using the HYSPLIT model and heat maps with QGIS; as well as integrating an index of pollutants to know the biological condition of the Sierra de Guadalupe.

4 Materials and Methods

4.1 Study Area

The study was carried out in the Sierra de Guadalupe, which is in the northern portion of Mexico City (CDMX) in Gustavo A. Madero mayor. It is between 2340 and 2980 meters above sea level (masl) and is considered a set of volcanic elevations formed in the Miocene [21]. Four study sites were selected, three within the Sierra de Guadalupe y la Armella Protected Natural Area (PNA) polygon and one outside the PNA, in an urban area (Fig. 1).

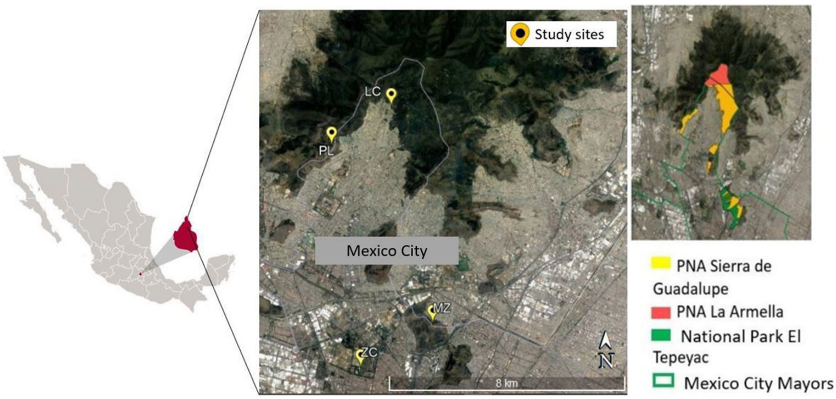

Fig. 1. Study area, Sierra de Guadalupe, CDMX, Mexico, and study sites

This area has not been completely studied, mainly in terms of air quality and the bird community. Sierra de Guadalupe is located in the northern part of Mexico City and is considered a relict natural site; however, it has been fragmented by settlements and various human activities, which place biological integrity and ecosystem services at risk [22]. Likewise, this site has been the refuge of a wide variety of resident and migratory bird species (96 species), as well as reptiles and flora, among other species [23]. Also, the PNA Management Plan Program notes that this site provides a variety of environmental services, such as CO_2 and suspended particles capture. These arguments lead to declaring this site (with particular biotic and abiotic characteristics) as a Protected Natural Area under the management category of Area Subject to Ecological Conservation.

The study sites La Caballeriza (LC) and El Panal (PL) are located within the PNA in the north, in these sites the predominant land use is conservation; however, there are urban settlements in the surrounding area [23]. On the other hand, the Site Zacatenco Module (MZ) is also located within the PNA polygon, on the hill of Zacatenco, on the side is the Mexico-Pachuca highway which has high vehicular traffic. Likewise, this site presents the use of conservation land and regular and irregular urban settlements (16). The Zacatenco Sports Zone (ZC) site is located outside the PNA polygon, in an urban area with urban and industrial settlements [24].

4.2 Birds Census

A bird census was conducted during the cold dry season (Jan-Feb 2020), at four study sites in the Sierra de Guadalupe, CDMX (MZ, LC, PL, and ZC). Three 30-meter-long transects were drawn at each study site, and birds that were seen or heard were recorded over a 10 min period, with the help of binoculars, cameras, and identification guides.

The survey was also conducted between 8 am and 11 am. The characteristics of the habitat (soil, understory, midstory, canopy, forest, forest shore, non-forest), the activity they were doing (singing, eating, flying, jumping between branches, etc.), food preference (insectivorous, granivore, frugivore, nectarivorous, carnivorous, omnivorous) and food stratum (foliage, soil, air, bark, water) were registered.

From a bibliographic review and the data recorded in the survey, a database was developed with the functional traits of each species.

4.3 Atmospheric Monitoring

Concentration data and AHI values of CO, O_3, $PM_{2.5}$, and PM_{10} were obtained from the atmospheric monitoring stations La Presa (LPR), Xalostoc (XAL), Gustavo A. Madero (GAM), Camarones (CAM), Tultitlán (TLI), and Tlalnepantla (TLA) of the Metropolitan Area of the Valley of Mexico and weather parameters (Relative Humidity, Wind Direction, Wind Speed, Air Temperature) using a portable weather station (DAVIS VantagePro) and an automatic weather station of the National Weather System.

4.4 Birds Community Structural and Functional Diversity

From the records of bird species, the values of species richness and abundance values were obtained, as well as Simpson diversity, Shannon diversity, maximum diversity, and evenness, with the following Eqs. (1, 2, 3 and 4).

Shannon diversity index

$$H' = \sum_{i=1}^{s} p_i Log_2 p_i \tag{1}$$

Simpson diversity index

$$D = 1 - \sum_{i=1}^{s} \frac{1}{p_i} \tag{2}$$

Maximum diversity index

$$H_{max} = \mathrm{Ln}(s) \tag{3}$$

Evenness index

$$J = \frac{H'}{Hmax} \tag{4}$$

Where:

- H_{max} = Sample information content (bits/individual)
- *H'* = Diversity Index
- *s* = Number of species
- *pi* = Ratio of the p_{esim} individuals of the species *i* with respect to the total individuals of the whole species in the community
- *D* = Probability that more organisms of the same species exist once the first has been collected
- *J* = Considers the *H'* diversity ratio of a place with respect to the maximum diversity that could be in that site

  Similarly, the functional diversity value of 25 functional trait metrics belonging to 7 categories of bird species life histories was obtained (Table 1).

  Functional diversity was assessed with the RAO coefficient from the following equation (Eq. 5):

$$FD = \sum_{i=1}^{s} \sum_{j=1}^{s} dij\, pi\, pj \tag{5}$$

Where:
FD = Functional divergence of food guilds
s = Number of species present in the community
pi and pj = Proportion of individuals of the species in the community
d_{ij} = Varies from 0 to 1.

Values close to 1 imply greater functional divergence or better use of the resources available in the environment; whereas, values close to 0 imply a greater overlap of niche in resource usage.

It was observed that data did not present normality neither homoscedasticity and significant differences between study sites were achieved through the non-parametric Kruskal-Wallis test.

4.5 Development of the Integrated Air Quality Index

The Integrated Air Quality Index (IAQI) was developed, based on an adaptation to the method of calculating the Integrated Biomarker Response [25]. This index was drawn up from the values of the AHI of CO, O_3, $PM_{2.5}$, and PM_{10} and the weather parameters of temperature, relative humidity, wind direction, and wind speed. The values were standardized with the next mathematical procedure [26]:

The average value from each parameter was obtained for each site (X) and the average value of each parameter for all study sites (m).

Table 1. Categories of selected functional traits

Class I	Habitat preference
Class II	Nesting
Class III	Food stratum
Class IV	Food guild
Class V	Sexual dimorphism
Class VI	Vulnerability value
Class VII	Residence category
Class VIII	Risk category
Class IX	Endemism category

The standard deviation value (s) of the average values of each study site (X) was obtained.

The value of Y was calculated with the next equation (Eq. 6):

$$Y = (X - m)/s \tag{6}$$

Z was obtained, where Z = Y or Z = −Y, as appropriate.

To get the value of S (score), the minimum value of each of the parameters from all the study sites was firstly calculated and the absolute value of the study site was added to Z (Eq. 7):

$$S = Z + |Min| \tag{7}$$

The value of S was represented with a radial plot, where each vector represents one of the air quality parameters. The area of the triangle defined for two successive parameters, with k parameter values, was obtained with the following Eq. (8):

$$A_i = S_i \times S_{i+1} \times \sin\left(\frac{2\pi}{k}\right)/2 \tag{8}$$

Whereas, the value of IAQI was calculated with the following Eq. (9):

$$IAQI = \sum_{i=1}^{k} Ai \tag{9}$$

Where:

Ai = triangle area value

S = parameter score value

k = total number of parameters.

Higher index values indicate higher air pollution or poor air quality.

The relationship between the structural and functional diversity of bird community and IAQI was assessed by a Principal Component Analysis.

Besides, the HYSPLIT atmospheric transport and dispersion model of particles (including PM_{10} and $PM_{2.5}$) was made through IMO-NASA satellite imagery. On the other hand, heat maps were made with the AHI values of CO, O_3, $PM_{2.5}$, and PM_{10}, as well as with the parameters of temperature, relative humidity and wind speed with the QGIS software.

5 Results and Discussion

5.1 Birds Community

A total of 48 bird species were recorded at the four study sites during the January-February census. The highest species richness was observed at the MZ site and the lowest in PL. On the other hand, the ZC site presented the highest values of relative abundance, Simpson diversity, maximum diversity, and functional diversity; while Shannon's evenness and diversity were higher in PL.

The nesting category presented the highest FD values, while the risk category obtained the lowest value of FD.

5.2 Meteorological Parameters

The highest temperature was observed at the ZC site with mean values of 19.3 °C, in contrast, the MZ site had the lowest temperature values ($p \leq 0.05$) (Fig. 2). Also, the ZC site had the highest relative humidity percentage (61%) and the MZ site obtained the lowest relative humidity, no significant differences were found ($p \leq 0.05$) (Fig. 3). On the other hand, the highest wind speed was presented at the ZC site with 3.5 m/s and at the MZ site the lowest wind speed was presented, no significant differences were found ($p \geq 0.05$) (Fig. 4).

5.3 Air Quality

The highest values of CO, PM_{10}, and $PM_{2.5}$ were observed at the MZ site, while lower concentrations were observed at LC and PL sites. The AHI value of O_3 is the highest at the ZC site and the lowest values of this pollutant were presented in LC and PL. The highest IAS values of CO, PM_{10}, and $PM_{2.5}$ were observed at the MZ site, while lower concentrations were detected at LC and PL sites. The AHI value of O_3 was higher at the ZC site and the lowest values of the ZC pollutant were presented in LC and PL (Fig. 5, 6, 7, and 8).

The highest IAQI was presented at the ZC site, followed by MZ; while the best air quality was observed in LC (Fig. 9).

The HYSPLYT backward trajectories for particles (assuming PM_{10} and $PM_{2.5}$) occurs from southwest to northeast at 100 and 500 masl; and it is also possible to observe in Fig. 10, that particles at a higher altitude (1500–2000 m above the surface) comes from east showing pathways greater than trajectories at 100 and 500 masl.

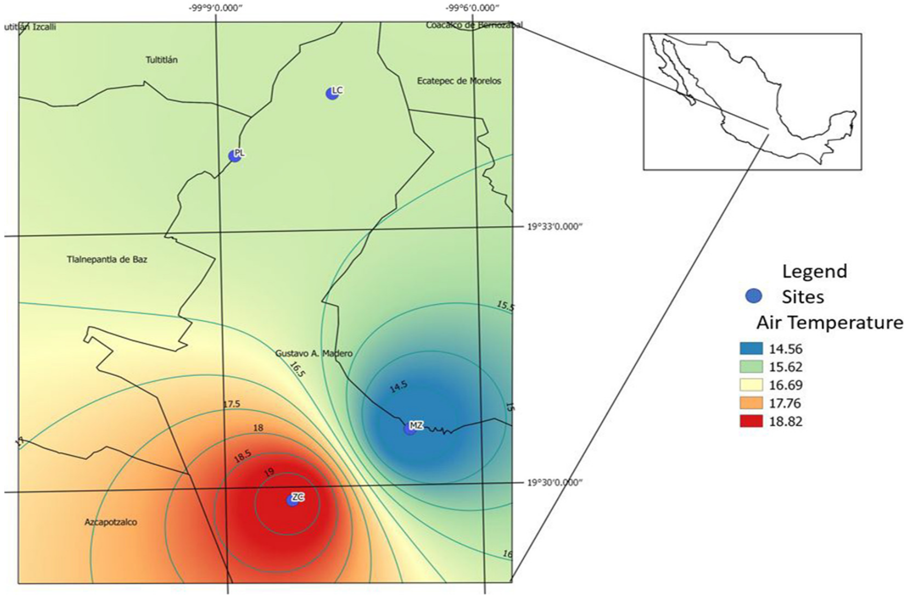

Fig. 2. Heat map for air temperature. Made with QGIS using Kriging technique.

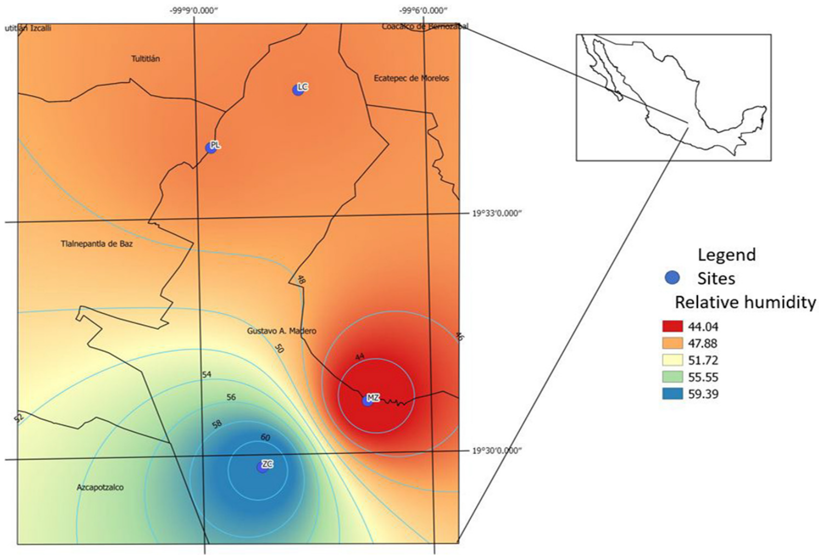

Fig. 3. Heat map for Relative Humidity. Made with QGIS using Kriging technique.

5.4 Principal Component Analysis

The biplot of the principal component analyses showed that the ZC site presented the highest values of temperature, relative humidity, air speed, IAQI, O_3, AHI, and functional

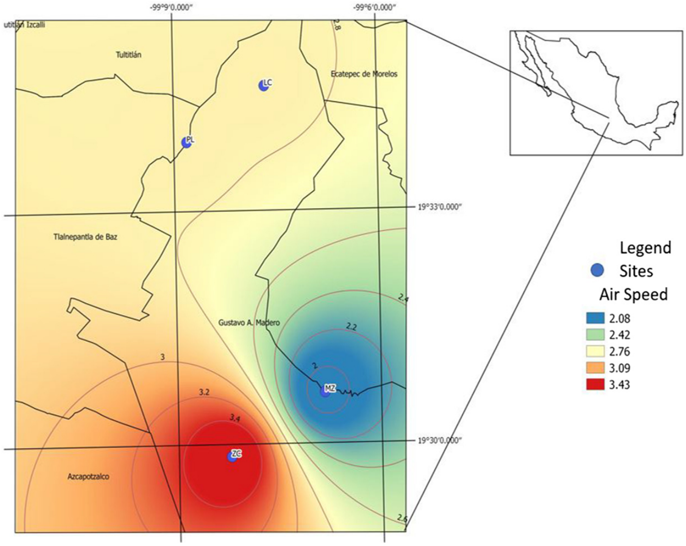

Fig. 4. Heat map for air speed. Made with QGIS using Kriging technique.

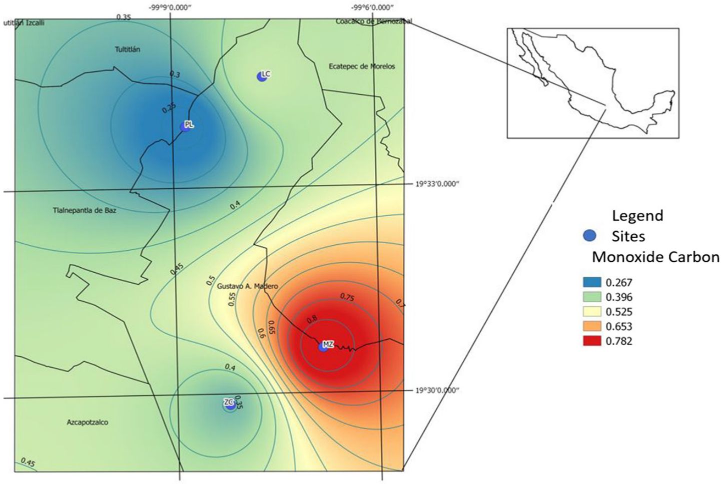

Fig. 5. Heat-maps for CO. Made with QGIS using Kriging technique.

diversity. While, the MZ site observed the highest concentrations of $PM_{2.5}$, PM_{10}, and CO, as well as the highest values of species abundance and specific richness. On the other hand, PL and LC sites had the highest air quality values, i.e. the lowest IAQI and AHI values (Fig. 11).

It is important to note that the ZC and MZ sites are located in the southern portion of the Sierra de Guadalupe and are the closest study sites to the urban area of the CDMX. The ZC site is located in an area with urban land use and industrial activity [24] but with

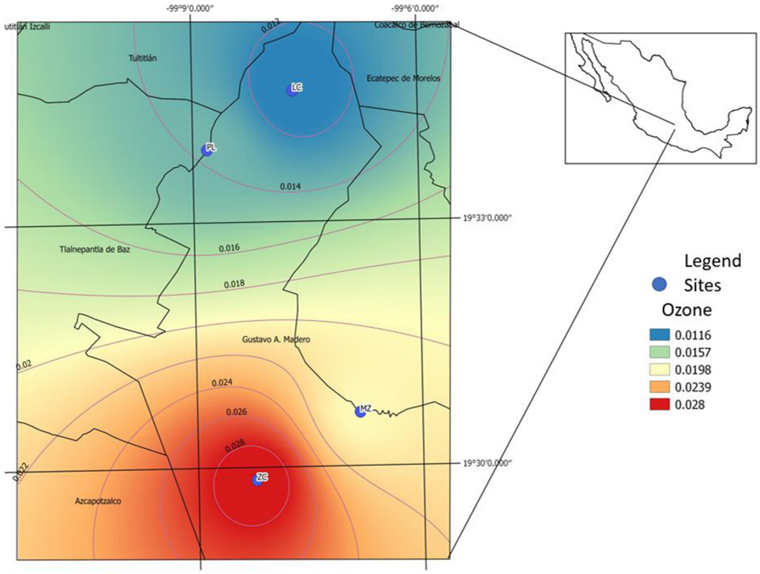

Fig. 6. Heat-maps for O_3. Made with QGIS using Kriging technique.

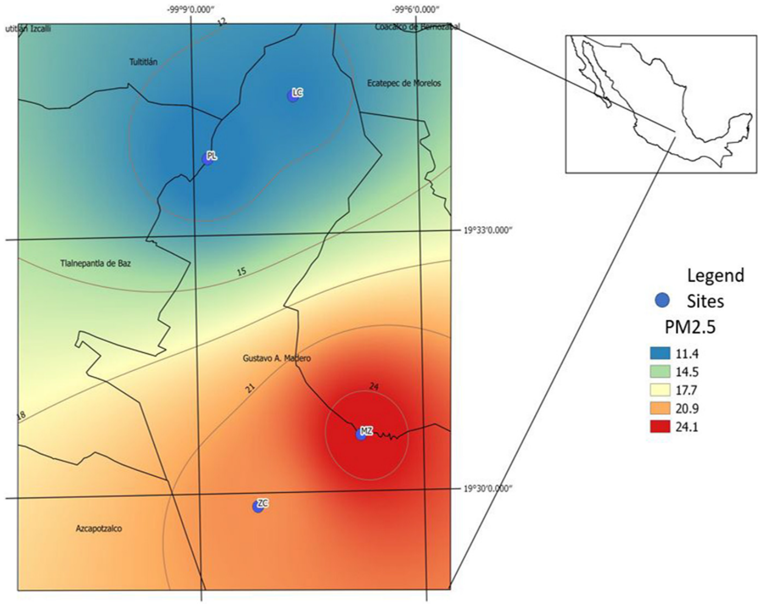

Fig. 7. Heat-maps for $PM_{2.5}$. Made with QGIS using Kriging technique.

large green areas, allowing the settlement of birds. On the other hand, the MZ site is part of the PNA Sierra de Guadalupe/La Armella, which has a land use of conservation;

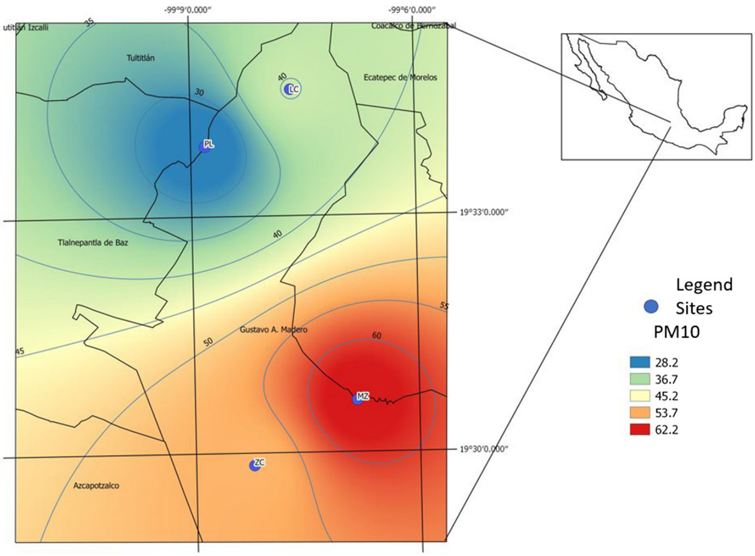

Fig. 8. Heat-maps for PM_{10}. Made with QGIS using Kriging technique.

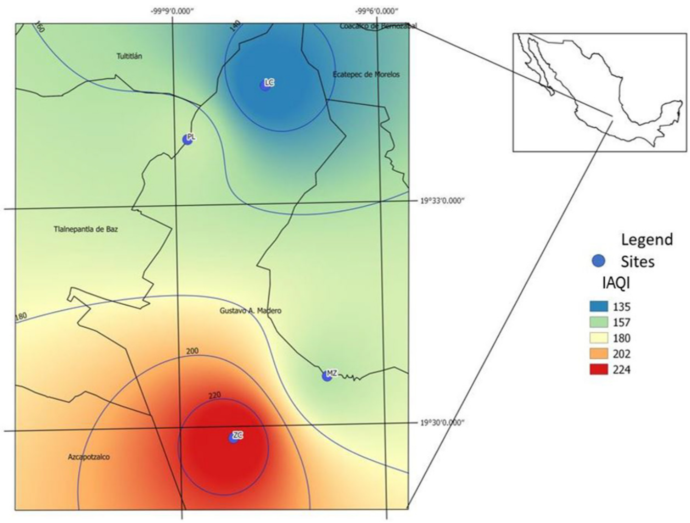

Fig. 9. Heat-maps of IAQI from the four study sites. Made with QGIS using Kriging technique.

however, this site presents some irregular urban settlements, besides on the Mexico-Pachuca highway is bordering this study site, which has a high vehicular transit [23]. Therefore, it is possible to say that due to the characteristics and anthropogenic activities carried out at both study sites, these have the worst air quality and therefore the worst biological condition.

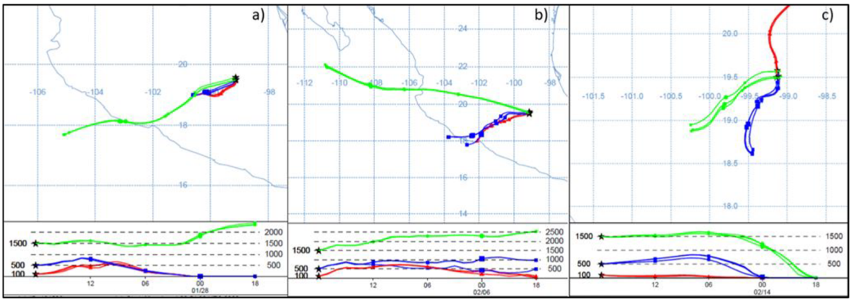

Fig. 10. HYSPLIT model runs (assuming particles as PM_{10} and $PM_{2.5}$) from the study sites, in a three-day monitoring a) January 28, 2020, b) February 6, 2020 and c) February 14, 2020.

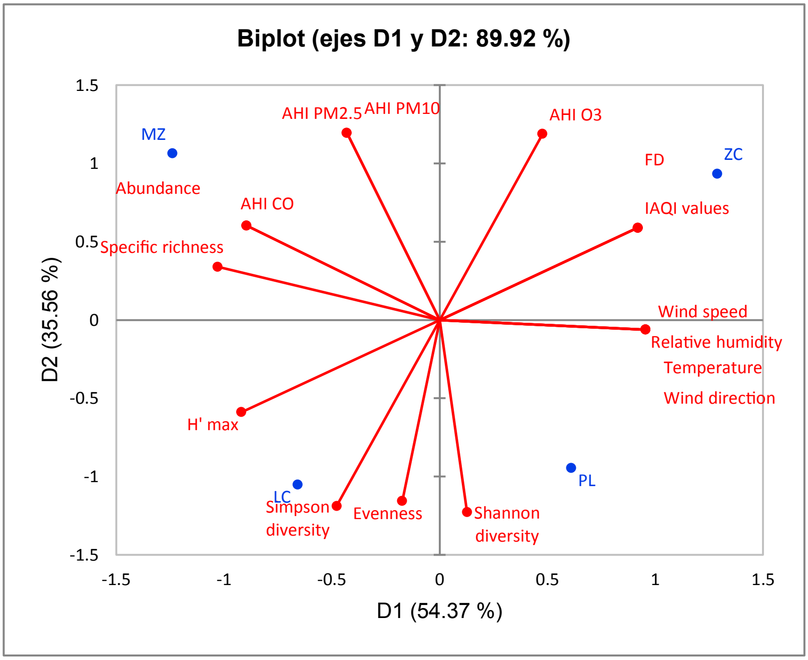

Fig. 11. Biplot of the Principal Component Analysis of the four study sites, meteorological parameters, AHI values, structural and functional diversity.

The CO, Particulate Matter, SO_2, and NO_x are known to be the main pollutants produced by mobile sources [27], which may be strongly related to the high vehicular activity of the MZ site. On the other hand, the highest mean value of temperature was found in ZC associated with the higher solar radiation that in the presence of NO_2 favors the production of O_3 [28], such a condition may explain the high values of this gas at that study site. Likewise, HYSPLIT modeling suggests that the movement of pollutants occurs from the southwest to the northeast, indicating pollutants trajectories impacting at the south of the Sierra de Guadalupe, where increased vehicular and anthropogenic activity is concentrated, contributing to raising pollutant concentrations in the southern sites (MZ and ZC).

On the other hand, the LC and PL sites are located within the polygon of the PNA Sierra de Guadalupe/La Armella, the predominant land use is conservation [23] also, anthropogenic activities are minor which, is related to the highest values of structural diversity (Simpson diversity, Shannon diversity, maximum diversity and evenness) and the best air quality (AHI and IAQI). Because of the above, it is possible to say that the sites with the best biological condition are LC and PL as they have a high species diversity and the best air quality. However, in contrast, the ZC site presents the highest functional diversity values, reflecting that the bird species recorded on this site have a lower overlap of niches and therefore use the available resources in a better mode than other study sites [8]. It is possible to state that birds can cope with adverse environmental conditions when they use the resources available in the medium appropriately.

Likewise, as mentioned above the nesting category obtained the greatest functional diversity, indicating that the bird species recorded in the four study sites have a high variety or diversity of traits associated with the species nesting type [29], such as the type of nest, the nest substrate, the number of eggs, the hatching time, among others. Therefore, it is possible to state that in general birds are taking advantage of the resources available to be able to cope with the conditions that arise and achieve reproductive success, facing various environmental conditions, which could be adverse [30]. As is the case with the ZC site, in which despite having the worst air quality and having high anthropogenic activity, functional diversity was the highest. The adaptation is defined as the anatomical, physiological and behavioral configuration of the species, given by natural selection. That is to say that the various characters are adapted to give it greater chances of survival [31]. In the case of urban birds or birds form sites that have facing alterations in natural conditions it has been observed that they carry out adaptation strategies, such as modifications in the vocalizations, which allow them to reproduce despite the high levels of noise [32, 33]. However, these studies were conducted in several surveys and at different seasons. Therefore, a long-term study in our study area is needed to identify adaptations in the bird analyzed.

The IAQI could be validated with external study sites from the ANP Sierra de Guadalupe; through bird census in different seasons. Likewise, continuous monitoring of CO, O3, PM2.5, PM10, relative humidity, wind direction, wind speed, and air temperature. Data validation will be performed with the comparison between the AHI values and an index that evaluates habitat quality, through a correlation and linear regression analysis.

6 Conclusions

The MZ and ZC study sites were the sites with the poorest air quality and biological condition, due to the geographical, climatic, and high anthropogenic activity that develops in these sites and their immediate surroundings. In contrast, the sites displaying the best air quality were the LC and PL, which have low anthropogenic activity, in addition to being immersed in the PNA polygon and support a greater structural diversity of bird communities. Also, the higher functional diversity was detected in the ZC bird community, suggesting that birds show divergence in the use of available resources in this area.

Due to the above, it is possible to claim that the PNA Sierra de Guadalupe/La Armella, which is one of the remnants of the natural sites of the CDMX, functions as a buffer zone and a remarkable biological conservation zone. Likewise, this study allows reaffirming the importance of green areas in the CDMX, since, sites such as ZC that, despite being in an urban area with industrial activity, function as a refuge for various species of birds. It is also possible to conclude that birds are good indicators of environmental quality, and in this case, of air quality.

On the other hand, it is possible to conclude that an integrated index of air quality (IAQI) associated with the structural and functional diversity of the bird community allows us to assess the biological condition of ecosystems and therefore allows us to alert promptly the possible damage to health, biodiversity, and ecosystems.

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