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Integrated Environmental Analysis of Air Quality, Meteorological Variables, and Bird Community in a Subtropical Urban Area

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Abstract

Objective of the study: to carry out an integrated environmental analysis of air quality, through the monitoring of atmospheric pollutants, meteorological variables and avifauna composition, in the municipality of Gramado, RS.

Methodology/approach: The study was carried out in an urban area in the city of Gramado/RS. The sampling period occurred between November/2021 and October/2022. For the collection of particulate matter (PM2.5 and PM10) a dichotomous sampler was used, with 24 collections being carried out. Meteorological data were provided by the INMET station. To survey the avifauna, 12 field trips were carried out, using the walking method.

Originality/Relevance: The knowledge produced by this study can contribute as a subsidy for strategies and actions aimed at better quality of life, health and environmental education.

Results: The results showed that two samples of PM2.5 and six samples of PM2.5-10 did not comply with the air quality guidelines established by the WHO. Using the linear regression model, it was found that 83.9% of the PM10 variation is explained by the increase in maximum temperature. Over the sampling period, the occurrence of 45 bird species was recorded. The highest species richness occurred in September/2022 (35) and October/2022 (32), where 37.4% of the variation in the number of birds can be explained by precipitation. For the other data there was no relationship.

Management contributions: The results can be used to carry out measures to promote environmental health, prevention and control of risk factors related to air quality.

Keywords: avifauna, atmospheric pollution, environmental quality, environmental health

Análise Ambiental Integrada da Qualidade do Ar, Variáveis Meteorológicas e Comunidade de Aves em Área Urbana Subtropical

Resumo

Objetivo do estudo: realizar uma análise ambiental integrada da qualidade do ar, por meio do monitoramento de poluentes atmosféricos, variáveis meteorológicas e composição da avifauna, no município de Gramado, RS.

Metodologia: O estudo foi realizado em uma área urbana no município de Gramado/RS. O período amostral ocorreu entre novembro/2021 a outubro/2022. Para a coleta do material particulado ($MP_{2,5}$ e MP_{10}) foi utilizado um amostrador dicotômico, sendo realizadas 24 coletas. Os dados meteorológicos foram disponibilizados pela estação do INMET. Para o levantamento da avifauna foram realizadas 12 saídas à campo, utilizando-se o método de caminhamento.

Originalidade/Relevância: O conhecimento produzido por este estudo pode contribuir como subsídio para estratégias e ações voltadas à melhor qualidade de vida, a saúde e educação ambiental.

Principais resultados: Os resultados demonstraram que duas amostras de $MP_{2,5}$ e seis amostras de $MP_{2,5-10}$ ficaram em desconformidade com as diretrizes de qualidade do ar estabelecidos pela OMS. Por meio do modelo de regressão linear verificou-se que 83,9% da variação do MP_{10} é explicada pelo aumento da temperatura máxima. Ao longo do período de amostragens foram registradas a ocorrência de 45 espécies de aves. As maiores riquezas de espécies ocorreram em setembro/2022 (35) e outubro/2022 (32), onde 37,4% da variação do número de aves pode ser explicado pela precipitação. Para os demais dados não houve relação.

Contribuições: Os resultados poderão ser utilizados para realização de medidas de promoção da saúde ambiental, prevenção e controle dos fatores de riscos relacionados a qualidade do ar.

Palavras-chave: avifauna, poluição atmosférica, qualidade ambiental, saúde ambiental

Análisis ambiental integrado de la calidad del aire, variables meteorológicas y comunidad de aves en un área urbana subtropical

Resumen

Objetivo: realizar un análisis ambiental integrado de la calidad del aire, a través del monitoreo de contaminantes atmosféricos, variables meteorológicas y composición de la avifauna, en el municipio de Gramado, RS.

Metodología: El estudio fue realizado en un área urbana de la ciudad de Gramado/RS. El período de muestreo ocurrió entre noviembre/2021 y octubre/2022. Para la colecta de material particulado (PM2.5 y PM10) se utilizó un muestreador dicotómico, realizándose 24 colectas. Los datos meteorológicos fueron proporcionados por la estación INMET. Para el censo de la avifauna se realizaron 12 salidas de campo, utilizando el método de la caminata.

Originalidad/Relevancia: El conocimiento producido por este estudio puede contribuir como subsidio para estrategias y acciones encaminadas a una mejor calidad de vida, salud y educación ambiental.

Principales resultados: Los resultados mostraron que dos muestras de PM2.5 y seis muestras de PM2.5-10 no cumplieron con los lineamientos de calidad del aire establecidos por la OMS. Mediante el modelo de regresión lineal se encontró que el 83,9% de la variación de PM10 se explica por el aumento de la temperatura máxima. Durante el período de muestreo, se registró la ocurrencia de 45 especies de aves. La mayor riqueza de especies ocurrió en septiembre/2022 (35) y octubre/2022 (32), donde el 37,4% de la variación en el número de aves se explica por la precipitación. Para los demás datos no hubo relación.

Aportes a la gestión: Los resultados pueden ser utilizados para llevar a cabo acciones de promoción de la salud ambiental, prevención y control de factores de riesgo relacionados con la calidad del aire.

Palabras clave: avifauna, contaminación atmosférica, calidad ambiental, salud ambiental

Introduction

"Studies regarding air quality and its association with environmental health, not only in Brazil but worldwide, have demanded an increasing and necessary commitment from governmental authorities to implement actions for controlling and preventing environmental risks that negatively impact health (National Health Foundation [FUNASA], 2020; Dapper et al, 2016). Particulate matter at levels above permissible limits can cause various health damages, including cardiovascular, cerebrovascular (stroke), and respiratory issues, by deeply penetrating the lungs and entering the bloodstream, with emerging evidence suggesting that particulate matter affects other organs and also causes other diseases (Dapper et al. 2016; São Paulo Environmental Company [CETESB], 2023; PAHO, 2022;). Thus, it is of paramount importance that studies aiming to understand and detect changes in the determining and conditioning factors of the environment that interfere with health be conducted, so that preventive measures can be created accordingly.

Within this context, birds can be considered a relevant group of animals for assessing and monitoring the ecological consequences of environmental change (Cable News Network [CNN], 2022). Changes in the environment are often attributed to anthropogenic disturbances, such as pollution, changes in land use, or natural stress factors, such as drought or late spring frost (Holt & Mille, 2010). Research has found that birds are developing larger bills, legs, and ears, allowing them to better regulate body temperature as the planet warms (Cable News Network [CNN], 2022).

Furthermore, knowledge about the composition of avifauna in certain regions is of great importance due to the fact that these animals play decisive ecological roles in natural communities, acting as pollinators, seed dispersers, and regulators of populations of other animals, such as insects (Sick, 1997). According to Almeida and Almeida (1998), wild birds are recognized as the best bioindicators of terrestrial ecosystems, especially those with forest habits. So far, there are no known studies for the Region of the Hydrangeas regarding the association of birds with air quality.

In a study conducted in the city of Pelotas/RS, it was found that increasing urbanization causes negative effects on avifauna, especially in cities considered medium-sized, where both species richness and abundance decrease as urbanization increases (Sacco et al., 2015). In

Uberlândia/MG, a study based on the analysis of micronucleus frequency in birds found that some species can be used as bioindicators of air pollution (Baesse, 2019).

According to Sanderfoot and Holloaway (2017), there is consistent evidence of adverse health impacts on birds attributable to exposure to atmospheric pollutants in both gaseous and particulate phases, including carbon monoxide, ozone, sulfur dioxide, smoke, heavy metals, as well as mixtures of urban and industrial emissions, which can reduce population density, species diversity, and species richness in bird communities.

Activities such as combustion in boilers, which are fixed sources, and vehicular emissions, which are mobile sources, promote a significant introduction of atmospheric pollutants into the air (Crispim et al., 2012; State Foundation for the Environment [FEAM], 2023). The Region of the Hydrangeas, located in the state of Rio Grande do Sul/Brazil, especially in tourist municipalities like Gramado and Canela, have the potential to generate atmospheric pollution due to the large influx of tourists, concentrated during certain times of the year.

Thus, the objective of this study was to conduct an integrated environmental analysis in an urban area in the municipality of Gramado/RS, through year-long monitoring of the presence of atmospheric pollutants, specifically PM2.5 and PM10, meteorological variables including precipitation, relative humidity, and maximum and minimum temperatures, and the richness and composition of the bird community in the urban area of the municipality of Gramado.

Theoretical Framework

Environmental Bioindicators

Monitoring air pollution through the responses of living organisms, such as bioindicators, can be a useful approach for environmental monitoring (Azzazy, 2020). Bioindicators are diverse living organisms, such as lichens, plants, and animals, used to assess environmental quality. They can be defined as living organisms that exhibit particular symptoms or responses indicating changes in some environmental influence, usually in a qualitative manner

(Hawksworth & Colwell, 1992).

The technique in which bioindicators are used can occur in a broader sense when working with populations and communities in a location, and in a more applied sense, working only with species. This methodology can occur in two ways - active, when the bioindicator species already exist in the location, as a result of an assessment of the organisms inhabiting the study area, and passive, when the species is cultivated or raised in an unpolluted environment and exposed to pollution for a specified period, with previously prepared species being exposed in the environment (São Paulo Environmental Company [CETESB], 2015).

The basic objective of research on bioindicators is to find species that can reliably detect environmental disturbances and demonstrate how these disturbances affect other species or biodiversity as a whole (CHOWDHURY et al, 2023). The advantage of using bioindicators as a method for assessing environmental quality lies in their low cost compared to physical-chemical sampling, which has a high cost and is ineffective at detecting changes in the natural environmental conditions of systems when they are subjected to diffuse disturbances. Bioindicators have an instantaneous analytical character, considered insufficient for characterizing ecosystem responses to pollution. Furthermore, bioindicators can be used for the cumulative assessment of events occurring over a certain period of time, retrieving an environmental history not detectable or measurable by other methods (Ottoni, 2009; CETESB, 2021; Chowdhury et al, 2023).

Air pollutants

Air pollution is one of the main risk factors for global morbidity and mortality, described as the presence of harmful materials in the air, caused by anthropogenic sources, in quantities capable of producing detrimental effects on human health and the ecosystem. It is responsible for increased incidence and deaths from various diseases, such as cardiovascular diseases, and contributes to global warming and consequent climate change and environmental imbalances, becoming one of the main problems in the world today (Nevers, 2000; Santos et al., 2021).

Air pollution is a mixture of hazardous substances from both natural and human sources, and atmospheric pollutants can be considered as any form of matter in quantity, concentration, time, or other characteristics that can make the air unsuitable or harmful to health, inconvenient for public well-being, harmful to materials, flora, fauna, and safety (Brazil, 2018; National Institute of Environmental Health Sciences [NIH], 2023). However, the main emissions of atmospheric pollutants come from human activities, with major sources in urban areas being vehicle traffic and industries (Guarnieri & Balmes, 2014; Santos et al., 2021).

The level of air pollution is measured by the amount of pollutant substances present in the air. The variety of substances that can be found in the atmosphere is vast, making it difficult to establish a classification. Thus, pollutants are divided into two categories - primary pollutants, those emitted directly from emission sources, such as sulfur dioxide (SO2), nitrogen oxides (NOX), carbon monoxide (CO), carbon dioxide (CO2), methane (CH4), volatile organic compounds (VOCs), polycyclic aromatic hydrocarbons (PAHs), and particulate matter (PM). Additionally, these materials are transported, diluted, and chemically and physically modified in the atmosphere, becoming secondary pollutants, such as photo-oxidants like ozone (O3) and peroxyacetyl nitrates (PANs) (CETESB, 2021).

Thus, secondary pollutants are defined as forming in the atmosphere through chemical reactions between primary pollutants and natural atmospheric components, directly responsible for permanent lung damage and respiratory diseases in humans (Ministry of the Environment [MMA], 2020; CETESB, 2021).

The interaction between pollution sources and the atmosphere will determine the level of air quality, which will determine the occurrence of various effects of air pollution on receptors, including plants, animals, materials, and human health (Brazil, 2018). The group of pollutants that serve as air quality indicators, adopted universally and chosen due to the frequency of occurrence and their adverse effects, includes Total Suspended Particulates (TSP), Total Suspended Particles (TSP), Inhalable Particles (PM_{10}), Fine Inhalable Particles ($PM_{2.5}$), and Smoke (FMC). Under the general term Particulate Matter, there is a set of pollutants consisting of dust, smoke, and all kinds of solid and liquid material suspended in the atmosphere due to their small size (CETESB, 2021; LIU, 2018).

Atmospheric particulate matter is a complex and heterogeneous mixture. Its distribution of physical size and chemical composition changes over time and space and depends on emission sources, atmospheric chemistry, and meteorological conditions (Liu, 2018). The chemical composition of PM mainly consists of nitrates and ammonium sulfates, metallic elements and earth crust elements, marine salts, carbonaceous material, and organic compounds, with $PM_{2.5}$ composed of nitrate, sulfate, ammonium, carbon, and organic compounds, trace metallic elements, and a high acidity concentration, containing primary particles generated by combustion processes from industries, vehicles, and secondary particles formed in the atmosphere from gases, while dust is the main source of PM_{10} (World Health Organization [WHO], 2005; Migliavacca et al., 2012; Ren et al., 2017).

The potential health problems caused by atmospheric pollutant particles are directly associated with their size, with smaller pollutant particles causing greater damage. Thus, they can be defined by this characteristic, where Total Suspended Particles (TSP) have an aerodynamic diameter of 50 µm or less and Inhalable Particles (PM_{10}) have an aerodynamic diameter of 2.5 µm or less. Smoke (FMC), on the other hand, is associated with particulate matter suspended in the atmosphere from combustion processes, where the smoke determination method is based on the light reflectance measurement incident on the dust. Exposure to smoke can cause health effects and worsen existing health conditions. (Air Pollution Control District [APCD], 2023; CETESB, 2021; WHO, 2022).

It is estimated that air pollution was globally responsible for approximately five million deaths in 2017, with approximately 70% of them resulting from external environmental air pollution (Santos et al., 2021). Thus, the National Environment Council [CONAMA] established National Air Quality Standards through Resolution No. 491 of 11/19/2018, to be used as one of the instruments for managing air quality, determining the concentration value of a specific pollutant in the atmosphere associated with an exposure time interval, to preserve the environment and the health of the population regarding the risks of damage caused by air pollution (Brazil, 2018; State Foundation for Environmental Protection [FEPAM], 2021).

Birds and air pollution

Birds represent one of the vertebrate animal groups with the highest species richness, ranking second in Brazil, behind only fishes, with a total of 1,971 species already recorded (Brazilian Council of Ornithological Records [CBRO], 2021). However, 236 taxa are threatened with extinction (Institute of Science and Technology in Biodiversity [ICMBIO], 2018; Pacheco et al., 2021). They form a group of animals that are well-known indicators of environmental health, due to their physiology and behavior (Liang et al., 2020).

Birds exhibit distinctive morphological characteristics, such as bodies covered by plumage composed of feathers and the presence of air sacs in their respiratory system (Sschachner et al., 2014; Bianchi et al., 2016). With a unique respiratory system, birds are particularly susceptible to pollution; hence, they are a useful taxon for monitoring ecosystem contamination, especially air pollution (Liang et al., 2020).

Therefore, birds are considered efficient bioindicators, also due to their behavioral characteristics, diversified diet, and utilization of various vegetation layers, including in contaminated environments; moreover, different species can be useful due to their bioaccumulation capacity (Baesse et al., 2019; Hurtado et al., 2020). In birds, heavy metals can be bioaccumulated in blood, feathers, liver, kidneys, bones, and eggs, impairing reproduction and the health of these animals. Heavy metals can also cause delays in embryonic development and morphological alterations in the nervous, cardiovascular, respiratory, digestive, integumentary, and sensory systems, as well as being associated with higher mortality rates (Hurtado et al., 2020; Goutner, 2001).

According to Dutta (2017), air pollution compromises the quality of life of birds, as these animals have narrow pulmonary capillaries and higher respiratory rates, spending a considerable amount of time outdoors. Therefore, they are highly vulnerable to atmospheric particles.

Based on a literature review, Sanderfoot & Holloway (2017) analyze consistent evidence of adverse health impacts on birds attributable to exposure to gaseous and particulate air pollutants, including carbon monoxide (CO), ozone (O_3), sulfur dioxide (SO_2), smoke, and heavy metals, as well as mixtures of urban and industrial emissions. According to the authors, bird responses to air pollution include respiratory difficulty, increased detoxification effort, elevated stress levels, immunosuppression, behavioral changes, and impaired reproductive success. Furthermore, this exposure to air pollution may reduce population density, species diversity, and species richness in bird communities.

et al. (2019) found that air pollution, particularly pollutants generated by urbanization and vehicle traffic, can affect bird health, using as methodology the analysis of micronuclei in these animals. This technique can assess the sensitivity of organisms to contaminants, based on a cytological technique used to access DNA, serving as a biomarker for DNA damage.

Moreover, a study in the United States (Liang et al., 2020) developed a monthly database, based on monitoring changes in air pollution and bird abundance in the same region, also tracking contemporary changes in climatic elements, including temperature and precipitation. Thus, they estimated the effect of ozone (O_3) and fine particulate matter ($PM_{2.5}$) on bird relative abundance in a single regression, where their estimates indicated that improvements in air quality over the past four decades have halted the decline in bird populations, preventing the loss of approximately 1.5 billion birds, around 20% of the current total. These results highlight that, in addition to protecting human health, air pollution regulations have previously unrecognized and unquantified conservation co-benefits.

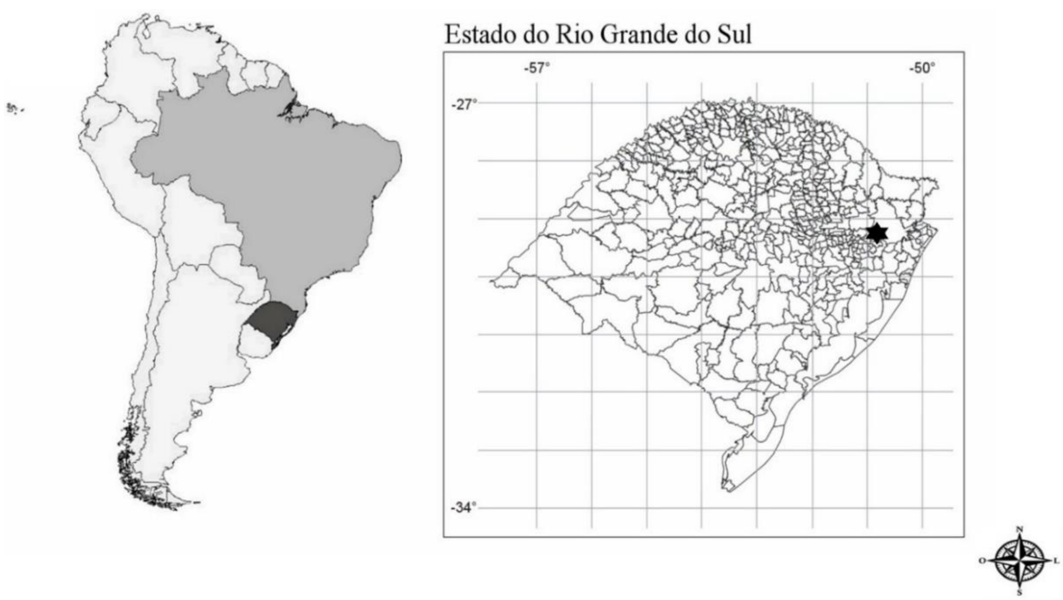
Methodology

Study Area

The work was carried out in the municipality of Gramado, RS (Figure 1), located in the Region of Hortênsias, which comprises five municipalities: Gramado, Canela, Nova Petrópolis, São Francisco de Paula (which also belongs to the Campos de Cima da Serra region), and Picada Café. Gramado has approximately 36,555 inhabitants and a territorial area of 239.338 km², with tourism as its main economic activity (Brazilian Institute of Geography and Statistics [IBGE], 2018).

Figure 1

Map locating the municipality of Gramado, RS

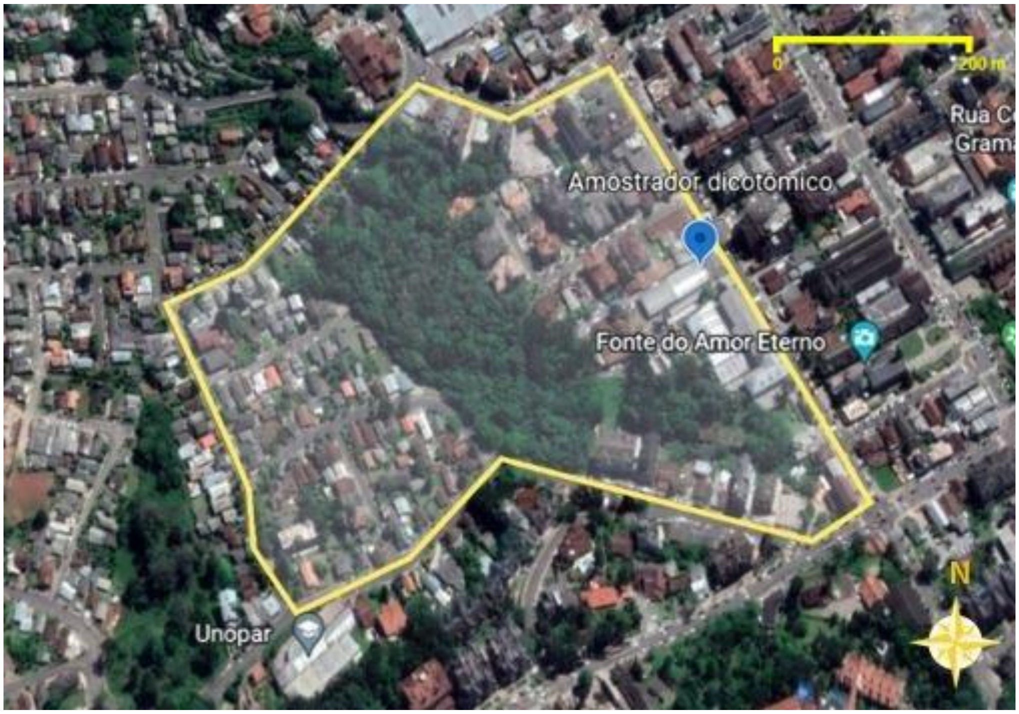


Source: The author (2022)

The site for collecting atmospheric pollutants, where the dichotomous sampler is installed, is located in a central area of the municipality, with heavy vehicular traffic and proximity to tourist-stimulating activities such as hotels and restaurants. The point, located at coordinates 29°22'44.67" South and 50°52'32.65" West, can be observed in Figure 2

Figure 2

The polygon delimited by the yellow line represents the area for bird monitoring. The blue marker indicates the location of the dichotomous sampler (29°22'44.67" South and 50°52'32.65" West



Source: Adapted from Google Earth (2023).

For the determination of bird community composition (richness) and structure, an area near the dichotomous sampler was selected. This area, as depicted in Figure 2, had its perimeter (marked in yellow) traversed during sampling. The delimited area encompasses 14.5 hectares and is characterized by the presence of a forest fragment within, surrounded by urban matrix, a remnant of disordered occupation in the municipality. The site features pronounced slopes and inclines, as well as a small body of water. The nearest urban matrix experiences heavy pedestrian and vehicular traffic, along with restaurants, hotels, and laundries located within 100 meters of the sampler, where combustion processes from boilers introduce particles into the atmosphere through fixed sources.

Monitoring and analysis of particulate matter

The monitoring took place over 12 months, starting in November 2021 and extending until October 2022. The filters of the dichotomous sampler were exposed in the collection equipment for 24 hours each month. Thus, 24 collections were carried out, with 12 corresponding to PM2.5 and another 12 to PM2.5-10. The filters were stored in a desiccator for 24 hours and weighed before and after sample collection to obtain the PM mass. They were stored at 5°C, wrapped in aluminum foil, according to Ceratti, 2021, to prevent degradation of PAHs (polycyclic aromatic hydrocarbons). Thus, the difference between the initial and final masses corresponds to the material deposited on the filter.

Filter weighing was performed using an analytical balance. For particulate matter collection, a dichotomous analyzer was used, as shown in Figure 3, which performs the inertial separation of fine and coarse particles through a virtual impactor. Upon entering the impactor, the sample flow is divided into two separate flow systems, and the air sample is fractionated, usually at a flow rate of 16.7 L/min, due to the acceleration that occurs in the particles. Thus, PM2.5-10 particles are directed directly to the first deposition chamber and deposited on a membrane filter, while PM2.5 particles are directed through a tube that channels the flow and are collected separately on another membrane (Costa et al., 2018).

Figure 3

Dichotomous sampler located in the municipality of Gramado, RS (29°22'44.67" South and 50°52'32.65" West)

Source: The author (2022).

Meteorological Data

Meteorological data for the analysis in this study were obtained from the meteorological station of the National Institute of Meteorology [INMET] located in the municipality of Canela, as it is the data supplier station for the Hortênsias Region and due to its proximity to the selected point, thus covering the entire study area. The station identified as Canela A-879, OMM code 86990, is located at an altitude of 831 meters, with coordinates latitude -29.368788º and longitude -50.827231º. The parameters used are provided from 11:00 AM to 8:00 PM and include temperature, relative humidity, and precipitation.

Avifauna Survey

For field sampling, the "transect" method described by Filgueiras et al. (1994) was applied, adapted for bird observation, where species are recorded through visual sightings and vocalizations along a route. Sampling campaigns were conducted over a period of 12 months, occurring once per month, near the area where the air quality sampler is installed, in the morning and afternoon periods, from 7:00 AM to 10:00 AM and from 6:00 PM to 9:00 PM, enabling the identification of species at different times. The transect was carried out randomly in the selected area (Figure 1), covering approximately 3 km per sampling.

Species were identified with the aid of a Bushnell 10x50 binocular and a voice recorder (Samsung A11). Images were captured with a NIKON COOLPIX P510 camera - 4.3-180mm lens, for later identification. Identification guides such as those by Gabriel Rocha (2015) and Narosky & Yzurieta (2003) were used to assist in identifications. The taxonomic classification of birds follows the Brazilian Committee of Ornithological Records [CBRO], (2021). Based on field sheets, a taxonomic list was prepared, accompanied by the monthly record of occurrence (presence or absence) of each species.

Statistical Analyses

For the integrated analysis of atmospheric pollutant presence, descriptive statistics were used, including mean, median, minimum, and maximum values. For meteorological data, descriptive statistics, including mean and standard deviation of the mean, were also employed. For avifauna survey, monthly occurrence of species present at the site, their presence or absence, was analyzed. In this study, we began to consider the multiple linear regression model, which was "estimated" using the Stepwise method, by SPSS 26.0 software.

Results and Discussion

Coarse and Fine Particulate Matter

Table 1 presents the concentrations of PM2.5 and PM2.5-10, including mean, median, maximum, and minimum values obtained for the sampling point. The results showed that two samples of PM2.5 and six samples of PM2.5-10 did not comply with the air quality guidelines established by the WHO. When compared to the guidelines of CONAMA 491/2018, one sample of PM2.5 and four samples of PM2.5-10 did not comply.

Table 1

Mean, median, maximum, and minimum concentrations found for PM2.5 (µg m^-3) and PM2.5-10 (µg m^-3) in Gramado from November 2021 to October 2022

Parameter	MP2,5		MP2,5-10
WHO	15		45
CONAMA 491/2018	60		120
	Period	**Gramado**	
	Nov/21	5,17	61,81(*)
	Dez/21	102,50(*)(#)	145,85(*)(#
	Jan/22	1,39	112,50(*)
	Fev/22	12,51	163,90(*)(#)
	Mar/22	12,19	150,01(*)(#)
	Abr/22	21,31(*)	120,84(*)(#)
	Mai/22	11,5	5,25
	Jun/22	6,92	2,67
	Jul/22	6,5	6,75
	Ago/22	7,92	2,67
	Set/22	0,42	0,92
	Out/22	6,42	4,92
	Mean	16,23	64,84
	Median	7,42	34,28
	Maximum	102,5	163,9
	Minimum	0,42	0,92
	Number of samples	12	12

Legend: (*) values above WHO; (#) values above CONAMA 491/2018. *Source:* The author, 2023

The highest concentrations for $PM_{2.5}$ occurred in December 2021 (102.50 µg m^-3) and

April 2022 (21.31 µg m^-3) and were found to be in disagreement with the air quality standards referenced by the WHO guidelines (15 µg m^-3). These months coincide with two important events in the city that attract a large number of tourists, namely, the "Natal Luz" (Christmas Light) and Easter, as the city is known for its chocolate manufacturing. Although Brazilian legislation (CONAMA 491/2018) establishes less restrictive conditions, WHO's global air quality guidelines were updated in 2021, establishing these new standards based on evidence regarding the health effects of air pollution (WHO, 2021).

Regarding $PM_{2.5\text{-}10}$, the six samples recorded between November 2021 and April 2022 showed concentrations that were not in compliance with values considered safe for public health by WHO (45 µg m^-3). Furthermore, four samples exceeded the limit recommended by CONAMA 491/2018 (120 µg m^-3), specifically in December 2021, February, March, and April 2022.

Air pollution substantially contributed to the global disease burden in 2015, which has increased over the past 25 years due to population aging, changes in non-communicable disease rates, and increased air pollution in low- and middle-income countries (Cohen et al., 2017). Health risks associated with particulate matter with a diameter equal to or smaller than 10 and 2.5 micrometers (µm), PM_{10} and $PM_{2.5}$ respectively, are particularly relevant to public health. Both $PM_{2.5}$ and PM_{10} particles are capable of deeply penetrating the lungs, but $PM_{2.5}$ can even enter the bloodstream, resulting primarily in cardiovascular and respiratory impacts and also affecting other organs (Pan American Health Organization [PAHO], 2021).

$PM_{2.5}$ was the fifth leading risk factor for mortality in 2015; its exposure caused 4.2 million deaths and 103.1 million disability-adjusted life years, representing 7.6% of total global deaths. Deaths attributable to $PM_{2.5}$ increased from 3.5 million in 1990 to 4.2 million in 2015 (Cohen et al., 2017).

In a study conducted in Recife/PE, it was found that reducing air pollutant levels to the new WHO limits would lead to a reduction of approximately 136.5 deaths in the municipality among individuals over 30 years old, 78 deaths in cardiovascular mortality (related to $PM_{2.5}$ reduction), and 30.9 deaths due to total non-external causes (related to PM_{10} reduction), as well as reducing 84 hospitalizations for respiratory or cardiovascular problems. These benefits represent a gain of 15.2 months in life expectancy for the population and a gain of almost US$ 160 million for the municipality (Leão et al., 2022).

Nearly 80% of $PM_{2.5}$-related deaths worldwide could be avoided if current levels of air pollution were reduced to the values proposed in the updated guideline, according to a quick scenario analysis conducted by WHO, with the greatest benefit observed in countries with high concentrations of fine inhalable particles ($PM_{2.5}$) and large populations (WHO, 2021).

Avifauna Survey

Throughout the sampling period, 12 observation campaigns were conducted, totaling 36 hours of sampling effort. During this period, it was possible to record the occurrence of 45 bird species, belonging to nine orders and 23 families. The taxonomic list and records are presented in Table 2.

Table 2

Taxonomic list, accompanied by the monthly occurrence record of bird species recorded from November 2021 to October 2022 in the municipality of Gramado, RS

Order/ Family	Species	Common name	N	D	J	F	M	A	M	J	J	A	S	O
Pelecaniformes														
Threskiornithidae	*Phimosus infuscatus*	Bare-faced Curassow			X	X	X	X	X	X	X	X	X	X
	Theristicus caudatus	Buff-necked Ibis	X	X	X		X	X	X			X	X	X
Cathartiformes														
Cathartidae	*Coragyps atratus*	Black Vulture	X	X	X	X	X	X	X	X	X	X	X	X
Charadriiformes														
Charadriidae	*Vanellus chilensis*	Southern Lapwing	X	X	X	X	X	X	X	X	X	X	X	X
Columbiformes														
Columbidae	*Columbina talpacoti*	Ruddy Ground Dove					X	X					X	X
	Columba livia	Rock Pigeon	X	X	X	X	X	X	X	X	X	X	X	X
	Zenaida auriculata	Eared Dove			X	X	X				X	X	X	X
Cuculiformes														
Cuculidae	*Crotophaga ani*	Smooth-billed Ani					X	X					X	
Apodiformes														
Trochilidae	*Eupetomena macroura*	Swallow-tailed Hummingbird										X	X	X
	Chlorostilbon lucidus	Glittering-bellied Emerald		X					X				X	
	Hylocharis chrysura	Gilded Hummingbird	X		X	X							X	X
	Amazilia versicolor	Versicolored Emerald	X	X		X	X	X	X			X		X
Falconiformes														
Falconidae	*Caracara plancus*	Southern Caracara				X								

	Milvago chimachima	Yellow-headed Caracara	X											
Picidae	*Colaptes campestris*	Campo Flicker								X				X
Psittaciformes														
Psittacidae	*Myiopsitta monachus*	Monk Parakeet	X	X	X	X	X	X	X	X	X	X	X	X
Passeriformes														
Furnariidae	*Furnarius rufus*	Rufous Hornero									X	X	X	X
	Cranioleuca obsoleta	Pale-breasted Spinetail										X		
Rhynchocyclidae	*Phylloscartes ventralis*	Mottle-cheeked Tyrannulet										X	X	X
Tyrannidae	*Elaenia mesoleuca*	White-crested Elaenia											X	
	Elaenia parvirostris	Small-billed Elaenia					X				X		X	
	Pitangus sulphuratus	Great Kiskadee									X	X	X	X
	Myiodynastes maculatus	Streaked Flycatcher		X					X					
	Tyrannus melancholicus	Tropical Kingbird	X	X	X	X	X	X	X	X	X	X	X	X
	Tyrannus savana	Fork-tailed Flycatcher	X	X	X	X	X					X	X	X
Vireonidae	*Vireo chivi*	Chivi Vireo												X
Hirundinidae	*Pygochelidon cyanoleuca*	Blue-and-white Swallow	X	X	X	X	X	X	X	X	X	X	X	X
Troglodytidae	*Troglodytes musculus*	Southern House Wren					X					X	X	X
Turdidae	*Turdus rufiventris*	Rufous-bellied Thrush	X	X	X	X	X	X	X	X	X	X	X	X
Mimidae	*Mimus saturninus*	Chalk-browed Mockingbird	X		X	X	X			X	X	X	X	X
Passerellidae	*Zonotrichia capensis*	Rufous-collared Sparrow	X	X	X	X	X	X	X	X	X	X	X	X
Parulidae	*Setophaga pitiayumi*	Tropical Parula			X	X	X	X				X	X	X

	Myiothlypis leucoblephara	White-browed Warbler	X		X	X						X	X	X
Icteridae	*Cacicus haemorrhous*	Red-rumped Cacique	X	X					X					
Thraupidae	*Rauenia bonariensis*	Gray-crested Finch											X	
	Paroaria coronata	Red-crested Cardinal							X					
	Tangara sayaca	Sayaca Tanager	X	X	X	X	X	X	X	X	X	X	X	X
	Sicalis flaveola	Saffron Finch	X	X	X	X						X	X	X
	Tachyphonus coronatus	Ruby-crowned Tanager	X	X			X					X	X	X
	Tersina viridis	Swallow Tanager											X	
	Coereba flaveola	Bananaquit	X	X	X	X	X	X	X	X		X	X	X
	Sporophila caerulescens	Double-collared Seedeater										X	X	
	Microspingus cabanisi	Cabanis's Hemispingus												X
Fringillidae	*Spinus magellanicus*	Hooded Siskin											X	X
Passeridae	*Passer domesticus*	House Sparrow	X	X	X	X	X	X	X	X	X	X	X	X
	Total	**45**	**21**	**19**	**20**	**21**	**23**	**18**	**18**	**15**	**16**	**28**	**35**	**32**

The author, 2023.

The total number of species (45) recorded for the municipality of Gramado corresponds to 6.39% of the bird species occurring in Rio Grande do Sul, when compared to the work of Franz et al., 2018, which records 704 species for the state. Only one study has been conducted in the municipality of Gramado on bird surveying, in two parks located in the urban area of the city, where after 72 hours of observation, 84 bird species were recorded, representing 11.9% of the avifauna recorded for Rio Grande do Sul (Joner & Barros, 2019).

There are numerous factors that can influence the results in a bird observation study, such as the sampling effort time, researcher experience, and equipment used, but in this research, the study location is highly relevant to the species richness recorded so far, since the chosen area is in the midst of an urban center, which attracts a large number of tourists daily. According to Teixeira & Barros (2015), in a bird survey conducted at Campus II of Feevale University (a fully urbanized area), 36 bird species belonging to 26 families were recorded, totaling 86 hours of observations.

We also observed that the increase in bird species occurred gradually from the month preceding spring, the breeding season for these animals, during which the state receives migratory species, such as Tyrannus savana.

Tomazelli et al. (2021) affirm that wild birds have greater potential to be used as environmental bioindicators in toxicity research, and suggest focusing on one or a few species whose ecological and physiological habits are well known.

According to Gonçalves et al. (2022), environmental disturbances, such as air pollution, disrupt communities and can lead to the extinction of some bird species or even generate mutagenic effects, such as Erythrocytic Nuclear Abnormalities (ENA), in individuals that remain in the environments. In the study by these authors, it was observed in relation to the experimental test that canaries from the urban environment presented higher quantities of ENA, demonstrating that poor air quality seems to be a favorable factor for the appearance of ENA in birds, and it is possible to use this biomarker in biomonitoring studies.

Furthermore, in a study using 12,921 breeding ducks, their contact with air pollutants, including fine particulate matter ($PM_{2.5}$), coarse particulate matter (PM_{10}), and total suspended particulate matter (TSP), was reduced, finding that the reduction of $PM_{2.5}$ was one of the important environmental parameters that affected the productive and reproductive performance of birds (Han et al., 2022).

According to Liang et al. (2020), there is large-scale evidence that air pollution is associated with a decline in bird abundance, and air pollution regulation that limits pollutant emissions, such as ozone, will bring substantial benefits for bird conservation and human health protection.

Meteorological Data

Table 3 presents data on meteorological variables, measured by parameters such as precipitation, average temperature, and relative humidity (average), obtained through the database of INMET, from the municipality of Canela/RS, from November 2021 to October 2022. The values are expressed as averages.

Table 3

Presentation of average values for meteorological variables from November 2021 to October 2022 for the municipality of Gramado/RS

Average Variables	Precipitation Total (mm)	Average Temperature (°C)	Relative Humidity (%)
Nov/21	5,12	17,33	78,02
Dec/21	1,93	20,28	72,95
Jan/22	9,4	24,74	63,4
Feb/22	1,9	23,16	65,86
Mar/22	2,8	22,27	73,2
Apr/22	0	18,95	80,04
May/22	6,34	10,72	85,85
Jun/22	12,99	9,96	87,6
Jul/22	172,6	14,55	79,72
Aug/22	327,2	11,59	82,58
Sep/22	170	12,38	81,8
Oct/22	182,4	14,07	84,32

The author, 2023.

Temperature variables for the study period recorded through the INMET station showed that the highest monthly average temperature was recorded in January 2021 (24.73°C), while the lowest monthly average was recorded in June 2022 (9.96°C).

Precipitation levels during the first eight months were scarce, as the lowest average concentration occurred in April 2021, where no rainfall accumulation was recorded. According to Castelhano and Mendonça (2019), when analyzing the relationship between rainfall levels and pollution values, particulate matter (PM) demonstrates particular relevance, as this pollutant showed its highest levels on days when there was no rainfall, as in the present study, where concentrations of PM2.5-10 were above the standards set by the WHO in the first six months of monitoring. Precipitation assists in "cleansing" the atmosphere, leaving it with lower concentrations of pollutants that can contribute to respiratory problems (Moraes et al., 2019; WHO, 2021).

Relative humidity reached its highest average value in June 2022, at 87.60%. According to the World Health Organization (WHO), relative humidity values between 30% and 50% are ideal levels for human health, but values above 65% can contribute to increased allergies, asthma, and upper respiratory tract diseases, while values below 20% represent alert and emergency states. Relative humidity and precipitation are key climatic factors in determining pollution levels; however, this depends on the pollutant being analyzed (Castelhano & Mendonça, 2019).

Analysis of Data Correlation

Table 1 presents the linear regression model relating data regarding bird survey and precipitation over the months from November 2021 to October 2022 for the municipality of Gramado/RS.

Table 1

Presentation of the regression model concerning bird survey and precipitation from November 2021 to October 2022 for the municipality of Gramado/RS

Coefficients [a]		Unstandardized coefficients	Standardized coefficients				Collinearity statistics	
Model		B	Error	Beta	T	Sig.	Tolerance	VIF
	(Constant)	19,5	2		10,6	<,001		
	Precipitation	0,03	0	0,61	2,45	0,03	1	1

Model Summary

Model	R	R-Squared	Adjusted R-Squared	Standard Error of the Estimate
1	,612[a]	,374	,312	5,23

Legenda: a. Variável Dependente: AVES.

Source: The author, 2023.

According to the linear regression model, 37.4% of the variation in the number of birds is explained by precipitation. Thus, in months with higher levels of precipitation, a greater number of birds were recorded. The positive correlation between bird richness and precipitation can be explained in several ways: urban birds may aggregate during rainy periods to stay warm, enhance group effect, avoid predation by urban felids, and also due to increased food availability. The effect of rain directly impacts vegetation, stimulating growth and increasing the availability of leaves, flowers, fruits, seeds, and indirectly, the associated invertebrate fauna, increasing the availability of resources for bird survival and reproduction (Eduardo, 2022). Additionally, the reproductive success of birds can be hindered by cold and drought under extreme conditions that may occur due to climate change (Crick, 2004).

According to Illán et al. (2014), precipitation and winter temperature predict long-term abundance changes in birds, posing a major challenge in predicting biodiversity responses to climate change. Rainfall is crucial for tropical taxa, shaping geographic and temporal biodiversity patterns in large portions of the globe, requiring further research to understand this relationship, as precipitation is changing in tropical latitudes more rapidly and less predictably than temperature (Boyle et al., 2020).

Table 2

Presents the linear regression model relating data on MP10 and maximum temperature over the months from November 2021 to October 2022 for the municipality of Gramado/RS

Coefficients [a]		Unstandardized coefficients	Standardized coefficients				Collinearity statistics	
Model		B	Error	Beta	T	Sig.	Tolerance	VIF
	Constant	138,95	29,47		-4,72	<,001		
	Precipitation	11,76	1,63	,916	7,209	<,001	1,00	1,00

Model Summary

Model	R	R-Squared	Adjusted R-Squared	Standard Error of the Estimate
1	,916[a]	,839	,822	28,79

The author, 2023.

The linear regression model found that 83.9% of the variation in MP_{10} is explained by the increase in maximum temperature. Thus, the higher the maximum temperature, the higher the concentration of MP_{10}.

Pollutant concentration is strongly related to meteorological conditions, and some of the parameters that favor high pollution levels are: high calm percentage, weak winds, and thermal inversions. This phenomenon usually occurs when nights are cold, and the temperature tends to rise rapidly during the day, causing a disruption in natural air cooling, characteristics present in the study municipality.

According to Lee et al. (2019), there may be excess positive and significant risks of death due to the synergy between high temperature and air pollution in the population for all pollutants. For this analysis, quasi-Poisson time series regression and meta-analysis were used to estimate the additive interaction between high temperature and air pollution. In a study conducted in India, consistently stronger associations were observed between atmospheric pollutants and mortality at high temperatures than at average temperatures. These differences were statistically significant for associations between PM_{10} and non-accidental mortality and between all pollutants studied and respiratory mortality (Qin et al., 2016).

Conclusions

The results of this study were significant as the objectives were achieved. A correlation between the bird community and precipitation was observed, highlighting the importance of rainy periods for bird reproduction. Furthermore, a correlation between atmospheric pollutants and meteorological variables, such as maximum temperature and levels of PM_{10}, was identified. It was concluded that higher concentrations of these pollutants occur during warmer months due to thermal inversion. It is suggested that future studies monitor temperature continuously throughout the day when collecting other data.

Although no correlation was found between the bird community and atmospheric pollutant concentrations during the study period, birds are known as bioindicators of air quality and are consequently affected by pollutants. Therefore, it is recommended to extend the monitoring period or focus on one or two bird species.

This study contributes to regional planning by providing an integrated environmental analysis of the consequences of the main economic activity in the studied municipality. The knowledge generated by this work can serve as a basis for further research on the topic and for the development of strategies related to public health and the environment. The assessment of both natural and urban environments, particularly regarding air quality, where pollutant levels were above WHO standards in several months, benefits not only the bird community but also the entire population of the municipality and the thousands of tourists who visit annually.

Furthermore, this study aligns with the Sustainable Development Goals, specifically Goal

11, "Make cities and human settlements inclusive, safe, resilient, and sustainable," and Goal 13, "Take urgent action to combat climate change and its impacts."

Regarding the limitations of this study, there was a lack of data on vehicle traffic, as the company responsible for vehicle entry into the municipality did not provide updated information for this research.

It is further suggested that future research on the topic focus on one or two key bird species, compare urban and rural areas for results, extend the bird observation period, and analyze the impacts of air pollution on species morphology through animal capture.

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