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Ecorc'Air: A Citizen Science Project for the Biomonitoring of Vehicular Air Pollution in Paris, France

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Key Points:

- We present the citizen science project Ecorc'Air, in which volunteers collect plane tree bark samples which are sent to laboratories
- The project has led to the production of annual maps since 2016 that identify variations in magnetic particle concentrations in Paris
- There is a growing interest and involvement in environmental research among urban dwellers, especially those involved in local associations

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Airborne particulate matter (PM) is known to have adverse health effects and is a growing concern in urban areas. Spatial and temporal variability is difficult to assess with the few air quality stations typically available in cities. As an alternative, tree bark acts as a passive captor on which PM is deposited. Magnetic susceptibility measurements can be used as a proxy indicator to estimate pollution from vehicle sources. We present the citizen science project called Ecorc'Air, in which volunteers collect plane tree bark samples, mainly in Paris, which are then sent to laboratories and used for various measurements. The project has developed since 2016, leading to the production of annual maps that identify variations in magnetic particle concentrations. The correlation between magnetic susceptibility and metal content has been verified using multi elemental analysis. Thanks to these numerous samples, we were able to identify areas with consistently high susceptibility values over time. We also quantified the decrease in susceptibility values with the distance between the tree and the road, as well as the shielding effect of parked cars on pedestrians. We showed trends in susceptibility variations over time along a specific well-sampled road, suggesting that this type of sampling and measurement could be used to quantify variations in metallic pollution at a local scale. Finally, through interviews, we found that there is a growing interest and participation of city dwellers, especially those involved in local associations, to act in favor of environmental research, as well as of municipalities to offer support.

Plain Language Summary Airborne pollution caused by particulate matter (PM) is a growing concern in cities because of its negative effects on health. Air quality stations in cities are too few to give a detailed image of the distribution of pollution. However, PM is also deposited on trees. Tree bark can then act as captors, and their magnetic properties can measure the quantity of metallic particles deposited on them, and give an estimate of the pollution from motorized traffic. Here we present the citizen science project Ecorc'Air, in which volunteers collect plane tree bark fragments, which are then sent to laboratories and used for various measurements. Since its beginning in 2016, the project has enabled the production of annual maps showing detailed concentration of metallic particles in Paris at a local scale. The quantity of particles decreases with the distance between the tree and the road, and parked cars can act as a shield for PM on pedestrians. Individual volunteers have different motivations than volunteers in groups or associations. Municipalities supporting the project consider citizen sciences as a way to connect with their citizens on environmental issues and a source of data for air quality quantification.

1. Introduction

Particulate matter (PM) pollution is a global key issue in urban areas all around the world. Fine particles (<10 µm: PM_{10}) are inhalable and represent a great danger, as they are easily absorbed into the human body and cause serious health problems such as cardiovascular and respiratory diseases (Pope et al., 2004). In France, $PM_{2.5}$ pollution is estimated to be responsible for 48,000 premature deaths per year, at a total cost of more than 75 million euros/year (French Senate commission of inquiry, 2015 available at: https://www.senat.fr/rap/r14-610-1/r14-610-11.pdf).

In European cities, vehicle use is widespread throughout the living space of residents and is the main source of PM pollution. The report published in 2019 by ANSES (French Agency for Food, Environmental and Occupational Health and Safety; https://www.anses.fr/fr/system/files/AIR2014SA0156Ra-Emission.pdf) gives a complete and recent review of the impact of vehicle traffic on the ambient air particles in urban areas in France, particularly

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around Paris. This report shows that the most harmful effects on human health are caused by soot, organic carbon and ultrafine particles (UFP <0.1 μm). There is strong evidence that these harmful effects are linked to exposure to vehicle traffic, which emits soot, $PM_{2.5}$ (fine particles <2.5 μm), road dust and diesel exhaust particles. Moreover, most of the transition metals such as Fe, Zn, Ni, Cu, and Va, known for their harmful effects, are also constitutive of the PM emitted by circulating motor vehicles. Therefore, the ANSES recommends decreasing these indicators, namely UFP, soot and organic carbon, which are not submitted to any limitation (whether at national or European level), in addition to the existing limitations on $PM_{2.5}$ and PM_{10}. Various modeling scenarios presented in the ANSES report have shown that technological developments of vehicles would reduce air pollution to some extent, but not enough to significantly improve urban air quality.

Current European Union legislation sets a threshold of 40 μg/m^3 over 1 year as the maximum level for average PM_{10} concentration, with no more than 35 days per year above 50 μg/m^3, while French legislation adds an alert threshold of 80 μg/m^3 of daily average. For $PM_{2.5}$, the annual average threshold is 25 μg/m^3. However, these values are superior to those recommended by the World Health Organization (WHO), which have been adjusted in September 2021 to 15 and 5 μg/m^3 concentration over a year for average PM_{10} and $PM_{2.5}$, respectively (https://iris.who.int/handle/10665/345329). While the EU and French limits were rarely exceeded in Paris in 2020, the WHO recommendation for $PM_{2.5}$ concentration is regularly exceeded for the inhabitants of Paris, as measured by Airparif, the air quality observatory in Paris (https://airparif.asso.fr/actualite/2021/impact-des-nouveaux-seuils-de-reference-de-loms-sur-lile-de-france).

Magnetic particles are present in PM from circulating motor vehicles, as Fe impurities in fuel and from wear and friction of engine components. These particles can also incorporate other toxic metals like Pb, Zn, Ba, Cd, and Cr into their structure (Harrison & Jones, 1995; Maher et al., 2008; Muxworthy et al., 2003). Therefore, the quantification of magnetic particles can be a fast and inexpensive alternative for monitoring anthropogenic air pollution. Several studies have reported a good correlation between magnetic susceptibility and heavy metal content (Bityukova et al., 1999; Hanesch & Scholger, 2002; Hoffmann et al., 1999; Lecoanet et al., 2003; Muxworthy et al., 2003; Petrovský et al., 2000). Measuring magnetic proxies has proved useful in producing maps in order to track PM air pollution in cities (e.g., Dawaï et al., 2021; Gautam et al., 2005; Mitchell & Maher, 2009). The use of passive biological sensors (tree leaves, bark, lichen, moss) has become popular because they are inexpensive, easy to use, widely available in cities, allow sampling at breathing height, and can provide a record of location-specific and time-integrated information on local air quality (see Hofman et al., 2017 for a review).

Citizen science is the participation of non-professional scientists in research, contributing to the generation of new knowledge and information (Bonney et al., 2014). The field of environmental science is one of the most popular for citizen science projects (e.g., Kullenberg & Kasperowski, 2016), with a strong and sometimes long tradition in ecology, and biodiversity monitoring (Lee et al., 2020). In contrast, citizen science in the geosciences has been developed more recently (Lee et al., 2020). In the field of air quality, the development of low-cost sensors promises the deployment of citizen measurement networks that will enable detailed mapping of air pollution (Schneider et al., 2017). However, the reliability of measurements from this type of sensors is often questioned (Schneider et al., 2017; Sokhi et al., 2022). The use of biomonitoring for air quality estimation is less common in citizen science but is interesting given the limitations of electronic sensors. Some projects use lichens as bio-indicators of air quality (Counoy et al., 2023; Seed et al., 2013; Tregidgo et al., 2013), which have proven their effectiveness in participative contexts since the 1970s (Gilbert, 1974). Furthermore, citizen science projects have recently been carried out to collect samples for magnetic characterization of PM (Leite et al., 2022; Letaïef et al., 2023), but a large-scale project using tree bark as bioaccumulators has never been implemented.

The participation of lay people in the production of scientific knowledge is seen as a way of involving people in issues that concern them (Bonney et al., 2016). This is the context in which the Ecorc'Air project was started: it is a regional citizen science project in the Paris region in which volunteers collect plane tree bark to use as passive biosensors for fine and ultrafine particles generated by urban activities, particularly road traffic. Based on measurements of the magnetic signal recorded by the barks, the associated laboratories provide the public and the authorities with an annual map highlighting the areas with the highest levels of magnetic particles. Ecorc'Air is part of PartiCitaE, a participatory observatory of the urban environment launched in 2016. PartiCitaE has been co-constructed with volunteers. A questionnaire and participatory meetings were used to define the priority development themes for the observatory (Turcati et al., 2022). Air quality was the most important issue for the people involved in the beginning of PartiCitaE. It should be noted that it is the volunteers who choose at which position the samples are taken, based on their knowledge of their local area, their perception of places that are more or less polluted, and the questions they have about (local) air quality. We also propose an annual meeting where we discuss with the volunteers about their choice where to collect samples and the questions we can answer with respect to the collected data. The link between PM concentration and road design presented in this article is one of these collectively discussed questions. Some committed volunteers also spontaneously suggest designing an easy-to-understand field sheet (Turcati et al., 2022), and others come to visit the lab or help with organization tasks. Considering all these elements of volunteers' involvement and co-construction of PartiCitaE, we argue that Ecorc'Air is a participatory science project according to the classification proposed by Haklay (2013).

The current manuscript reports on the conception and evolution of the Ecorc'Air project, first initiated in Paris in 2016, motivated by the larger project NanoEnvi (Leite et al., 2022; Macouin et al., 2023) and funded by a "Paris2030" project, over a 5-year period (2019–2023), as well as some of the results obtained during the preparatory and construction phases. The results presented in this manuscript deal with the measurement of magnetic susceptibility as a proxy parameter for PM concentrations as well as the perception of pollution and the motivation of the volunteers.

2. Methodology for the Laboratory Measurements

2.1. Sampling and Sample Preparation

While magnetic measurements using tree leaves have been widely used for biomonitoring (e.g., Mitchell & Maher, 2009), it was found that similar measurements using tree bark are preferable, as the magnetic signal is usually stronger, easier to collect by volunteers, and more representative of pollution in the human breathing zone. Tree bark have been used in previous elemental analysis of PM and have been found to be reliable biosensors (Chaparro et al., 2020; Dawaï et al., 2021; Moreira et al., 2018). In addition, the bark of species such as *Platanus* desquamates every year at approximately the same period when outside temperatures start to increase. Sampling each year at the same time (typically at the end of the winter) provides an integrated measurement over one full year. *Platanus* (*orientalis* and *hispanica*) is also the most common tree in Paris, with more than 40,000 specimens. They are often planted as tree alignments and can provide an excellent spatial resolution (of the order of 10 m) of measurements along specific transects.

The sampling protocol consists in detaching several fragments of the bark from the tree side exposed to vehicular traffic, at heights between 1 and 1.7 m, using a freezer bag turned inside out for each sample, to avoid contamination between samples and the transmission of potential diseases from one tree to another. The fragments are then stored in the freezer bag. Sampling multiple fragments allows averaging of measurements on the side of the trunk exposed to PM. Sampling must be carried out over a relatively short period of time (3–4 weeks) to ensure that the same period is sampled and that the results can be compared. If samples were collected wet, participants were instructed to let them air-dry for a few days before sending them to the laboratory. Therefore, processing was always performed on dry samples.

In the laboratory, samples are crushed using an agate mortar or a wooden and ceramic grinding mill, then transferred into a sampling box and weighted.

2.2. Magnetic Analysis

Low-field magnetic susceptibility is a reliable proxy indicator for quantifying vehicular ferromagnetic particles (e.g., Gautam et al., 2005), although the paramagnetic and diamagnetic contributions can be significant if the anthropogenic contribution to the magnetic signal is weak (Rochette, 1987). Measurement of magnetic susceptibility has been carried out using three different pieces of equipment depending on the laboratory where the measurement took place. Samples from the 2016 campaign were measured at the Complex Fluids Laboratory at University of Pau using an MFK1-FA Agico susceptibilimeter, while those collected during the 2019 campaign were measured at the Mines Paris-PSL in Fontainebleau using a Bartington susceptibilimeter. The latest samples from the 2020, 2021, 2022, and 2023 campaigns were measured by the research team at the Institut de Physique du Globe de Paris (IPGP) using an Agico KLY-3 susceptibilymeter (Kappabridge). The values were then normalized to mass. Some of the samples that were measured on the Bartington were re-measured on the

Kappabridge to check that results are independent of the susceptibilymeter used. We found that results were consistent within 5%, which is in agreement with the inter-calibration carried out by Sagnotti et al. (2003).

2.3. Multi-Elemental Analysis

The basic premise of using magnetic susceptibility as a proxy indicator for the presence of PM is the correlation of this magnetic parameter with the metal content in the bark, such as Fe, Pb, Zn, Cd, Ni, Cu, Cr (Cao et al., 2015; Carvallo et al., 2021; Mitchell & Maher, 2009). In order to check this assumption, elemental characterization was performed on about 100 bark samples collected during the 2020 campaign. One thousand mg aliquots of each bark sample powders were acid digested with a mixture of ultrapure HNO_3-HF-HCl after removal of refractory organic matter by carbonization at 500°C. The major elemental content (Fe, Mn, Al, Cr, Ni, Na, K, Mg, Ca, Si) was measured in all the samples after a first dilution in 2% ultrapure HNO_3 using ICP-AES (ICAP 6200, Thermo Fisher) at the IPGP. High-Resolution ICP-MS (Element II, Thermo Scientific) with multi-element standard solutions were used to measure concentrations below 10 μg L^{-1}. The ICP-AES generally has detection limits that range from 10 to 200 μg L^{-1}. The detection limits for the ICP-MS are typically between 0.006 and 0.074 μg L^{-1}. The measurements had standard deviations (1σ) lower than 5%. Certified values of metal concentrations measured in the Standard Reference Material 1,547 peach leaves and SRM 1515 apple leaves standards (NIST) were recovered at more than 95%.

2.4. Perception of the Pollution and Motivation of the Volunteers

As part of a student project run by five BSc students of University of Paris Science Lettres (PSL), six semi-structured interviews were conducted in 2021 with people involved in Ecorc'Air. Three interviews involved volunteers, one a group of high school-aged girl scouts and two employees of local authorities (Paris City Council and Nanterre City Council, a town in the north-west suburbs of Paris). The last two interviews were also group interviews, as in both cases two employees from each municipality were interviewed at the same time. The aim of the survey was to understand how volunteers perceive air pollution and what motivates them to get involved in the Ecorc'Air project. For the municipal employees, the survey also aimed to examine the potential political impact of their involvement in the program. Based on the data we currently acquired, the aim here is to document the beginnings of the involvement of these municipalities rather than to understand how this is changing public policy. The analysis of political and activist interest was completed based on testimonies collected by a local newspaper "Le Parisien" from the collective of residents of Versailles and an elected official from the town (https://www.leparisien.fr/yvelines-78/a-versailles-la-pollution-de-l-air-controlee-grace-a-l-ecorce-des-platanes-11-04-2021-8431008.php).

3. Development of the Ecorc'Air Project

3.1. Historical Background

The Ecorc'Air project was developed in several stages. The first sampling took place in February 2016 as part of the project Paris 2030: around 200 samples were collected over 5 days by six researchers and students. Initially, bark fragments were collected from two sides of the tree: the side exposed to traffic and the opposite side. As the magnetic signal was consistently much lower for samples taken on the opposite side, we decided to focus only on the traffic-exposed side of the tree. In February 2019, 87 samples were collected over 2 days by four researchers. These two sampling campaigns took place exclusively along the Seine River banks.

In late 2019, the project was named Ecorc'Air and joined the Participation Citadine à l'Observation de l'Environnement (PartiCitaE) scientific observatory hosted by Sorbonne Université, Paris, France. PartiCitaE is a research tool in its own right, but it is also a citizen science tool that ensures that the needs of society are taken into account in environmental research. Its aim is to build a global, scientific and shared knowledge of the urban environment, for both researchers and residents. For Ecorc'Air, a sampling protocol was defined and a fieldwork sheet was created to help participants record the necessary information for each sampling contribution. This information was made available on the Ecorc'Air web pages, which are integrated into the PartiCitaE website (http://www.particitae.upmc.fr/fr/ecorcair.html). The sampling campaign in March 2020 was used as a test for the protocol to be distributed to the participants: five volunteers from the PartiCitaE network joined the researchers and gave initial feedback on the sampling instructions given to the public. Thanks to this volunteer participation,

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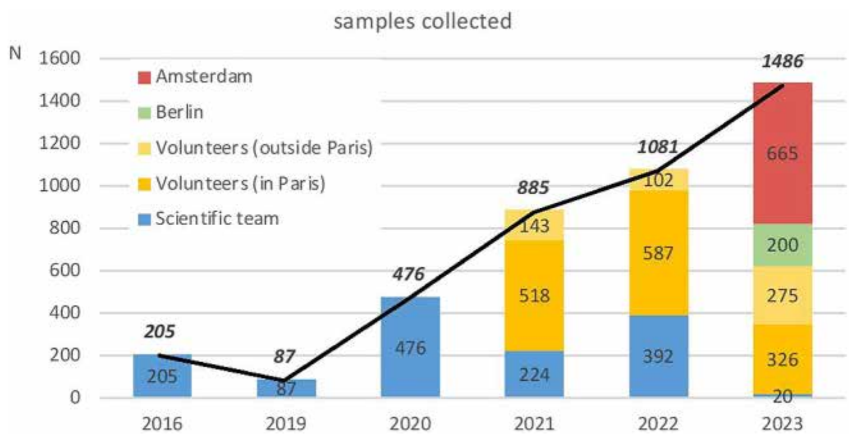

Figure 1. Number of samples collected during the Ecorc'Air project in the Great Paris area by scientific staff or French volunteers and cities abroad (in 2023 only).

476 samples were collected over 4 days with the help of the scientific team (Figure 1). The sampling area was extended to include six transects in addition to the Seine quays.

In order to gain visibility and participation, in 2021 we established contact with the City Council of Paris through its Air Quality Department (Pôle Qualité de l'Air) and Civic Engagement Department (Pôle Engagement et Vie Citoyenne). These two departments agreed to provide logistical support for the project by financing small items of sampling equipment, announcing the project via the network of «Volunteers of Paris», a community that can be called upon for punctual events requiring a large number of participants, and supporting the local district town halls, where sampling kits (freezer bags and sample identification sheets) were made available to participants. Due to the health restrictions associated with COVID, a videoconference was held to launch the field campaign by presenting the scientific project and explaining the sampling protocol to the participants. Around 70 volunteers attended the presentation, which took place in the beginning of April 2021 at the start of a new COVID-related lock-down period in France. Despite travel restrictions associated with COVID, we obtained 518 samples from volunteers in the Paris intra-muros, 57 samples from the suburbs near Paris and 86 from the city of Versailles, where a local association wanted to document the potential impact of a current urban planning project. Together with the 224 samples collected by the scientific team, the number of samples within Paris increased to 742. In 2021, a total of 885 samples were collected (in and outside Paris) (Figure 1).

In 2022, the City of Paris reaffirmed its support and gave Ecorc'Air greater visibility thanks to a presentation held at the «Climate Academy», a municipal structure that organizes events such as workshops, exhibitions or seminars on environmental issues. This gave us the opportunity to meet the volunteers face-to-face, to present the results from the previous year's campaigns and to explain the sampling protocol to the new volunteers. Sampling kits provided by the City of Paris were distributed at the end of the presentation and left for a month at the Climate Academy for the volunteers use. Over the course of a month, volunteers sampled 587 samples inside and 102 samples outside of the city of Paris, while the scientific staff sampled 392 trees, bringing the total number of Parisian samples to 979, the highest number of Parisian samples collected so far in this project (Figure 1).

Finally, in 2023, in order to test the appropriation of the project by the citizens, the scientific team did not participate in the sampling campaign (except for 20 test trees). Solely volunteers took samples. No instructions or guidelines were given on where to sample. The participants were fully free to select the sampling location based on their interests, driving the entire project. A respective information session was held at the Climate Academy, attended by approximately 35 volunteers. Sampling kits were provided to participants. Samples were either deposited at the Climate Academy or directly at IPGP Laboratory in a drop box, or sent by post to IPGP. After 1 month of sampling, we recovered 601 samples.

In the same year, students from Berlin, Germany, contacted the scientific team throughout the Circle-U framework, a consortium of nine European universities collaborating on research projects and teaching. Students from Humboldt University in Berlin collected 200 samples within the city, and one student traveled to the IPGP to perform the magnetic susceptibility measurements. We were also contacted by the Dutch Urgenda Foundation,

Figure 2. Sample identification sheet (left: original sheet in French; right: translation in English) to be filled by participants.

involved in the support of environmental projects in the Netherlands. Members of the Foundation collected and sent 665 samples from town all over the country. While the results from these samples are beyond the scope of this paper, they indicate a growing interest both from scientists and from non-governmental organizations in the Ecorc'Air project in other European countries (Figure 1).

3.2. Sampling Guideline for Participants

Information for participants is available on a website in French (https://particitae.sorbonne-universite.fr/les-programmes-de-particitae/ecorcair), which provides an overview of the study background, protocol details, and preliminary results from previous years. In 2022, we updated a map every week displaying the locations of samples gathered throughout the week. This allowed participants to focus on areas where samples were most required. Most of this information was presented in a brief video which was also available on YouTube (https://www.youtube.com/watch?v=lDf0JeLW2ao).

Communication was also carried out through the PartiCitaE social media channels, mainly through the newsletter, which reaches more than 500 subscribers a month, and the PartiCitaE Facebook page, which has 332 followers to this date.

The sample identification form is an essential part of this project (Figure 2). It is distributed to participants either printed out or through the Ecorc'Air website where it is available, and contains information fields to be filled in: the sampling date; the GPS coordinates (latitude and longitude) of the tree; the address and/or any information related to the localization, such as the proximity of traffic light, bus stop, bike lane, etc., and an open field for any other information. We also ask to record the distance between the tree and the nearest traffic line, and a measurement of the trunk size: the circumference at 1.3 m height (average sampling zone, equivalent to the breathing height of a pedestrian). The circumference can be used to find the tree in the event of a mistake in the GPS coordinates. The back of the sheet contains a summary of the sampling protocol and information on where to return the samples (Figure S1 in Supporting Information S1).

This sampling sheet was redesigned by a volunteer in 2020 and minor changes were made for the 2022 campaign, based on volunteer feedback to make it clearer: the diameter of the trunk was specified by selecting one of the suggested intervals: 0–50 cm, 50–100 cm or greater than 100 cm. The translation of the sampling sheet in Dutch was carried out by volunteers from Urgenda themselves.

4. Results

4.1. Magnetic Susceptibility as a Proxy Indicator of Metal Content

As mentioned above, magnetic particles emitted from circulating motor vehicle sources, not only contain the iron oxide that produce their magnetic properties, but they also carry over several heavy metals, incorporated to their

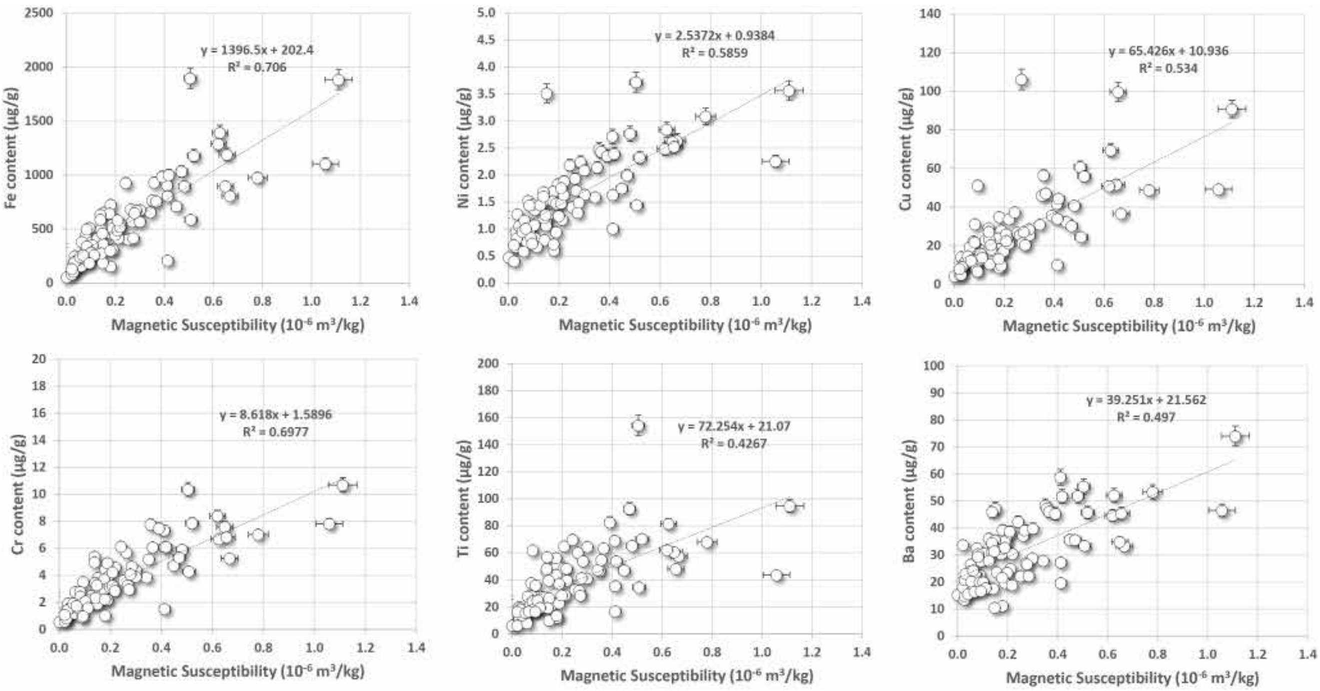

Figure 3. Total elemental content measured by ICPMS versus Magnetic susceptibility.

structures. As reported in previous studies for various sample types (Bityukova et al., 1999; Hanesch & Scholger, 2002; Hoffmann et al., 1999; Lecoanet et al., 2003; Muxworthy et al., 2003; Petrovský et al., 2000), there is a positive and significant correlation between magnetic susceptibility and total metal content observed in bark samples of the 2020 campaign (Figure 3). In addition to Fe, the contents of Ni, Cu, Cr, Ti, Al, Ba, and V in tree bark increase with the magnetic susceptibility, highlighting the relevance of this latter parameter to monitor metallic particulates from anthropogenic emissions in urban area.

4.2. Magnetic Susceptibility Mapping

The first objective of this work is to produce maps of magnetic susceptibility for different sampling years in Paris (Figure 4). Results were also presented as histograms (Figure 5). Finally, Table 1 summarizes the median, mean and standard deviation values for susceptibility for each year of sampling. These results are also displayed in Figure 6. The points of interest mentioned in this and in the next section are shown in Figure 7.

The map obtained for 2016 shows several zones along the Seine where susceptibility values are high (Figure 4a, dark red zones): the right bank of the western side of Paris, corresponding to the beginning of the western side of the Pompidou expressway built in 1967; the area just before the Eiffel Tower on the left bank; and the section between Châtelet Square, a busy square, and the Paris City Hall. Some high values were also observed between Place de la Concorde and Île de la Cité. Values range from 0 to 0.82×10^{-6} m^3/kg, with an average value of 0.20×10^{-6} m^3/kg (respectively -6 and -6.7 in log scale (ls)). It should be noted that the lowest values are most likely influenced by the diamagnetic contributions carried by the biological matrix (tree bark) or the environmental paramagnetic contribution (e.g., mineral soil dust) of some specific sites and therefore represent the background of samples that are not or very little contaminated by circulating motor vehicles pollution.

Despite the lower sampling density in 2019, the distribution of susceptibility values appears to be generally slightly lower than those measured at the same locations in 2016 (Figure 4b). In particular, the susceptibility values along the Pompidou Expressway are one to two times lower than the previous year (Figure 8). On the contrary, the area along the Jardin des Tuileries showed an increase in susceptibility. All the values obtained in 2019 range from 1.20×10^{-8} m^3/kg (ls: -7.9) to 1.38×10^{-6} m^3/kg (ls: -5.9), with an average value of 0.17×10^{-6} m^3/kg (ls: -6.8).

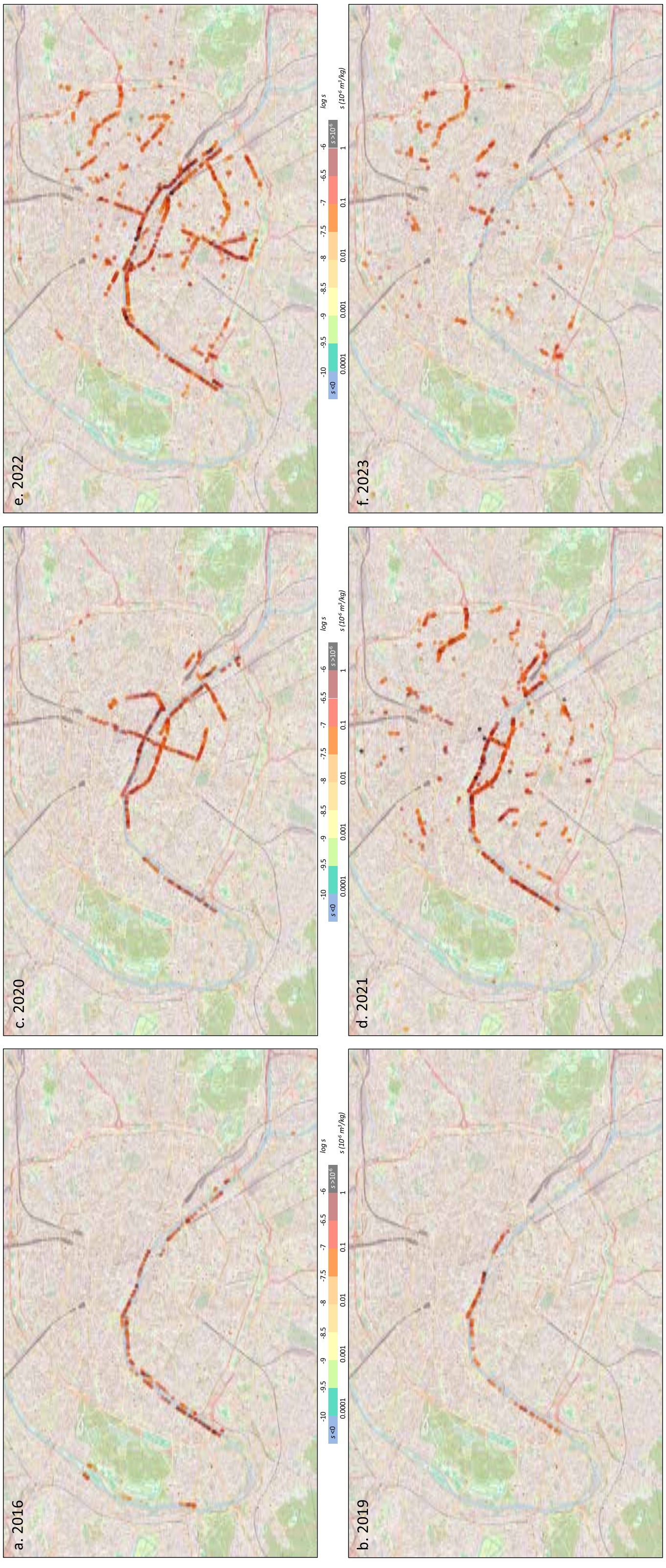

Figure 4. Magnetic susceptibility values for tree bark samples collected in Paris from 2016 to 2022. The logarithmic color scale is identical for all maps.

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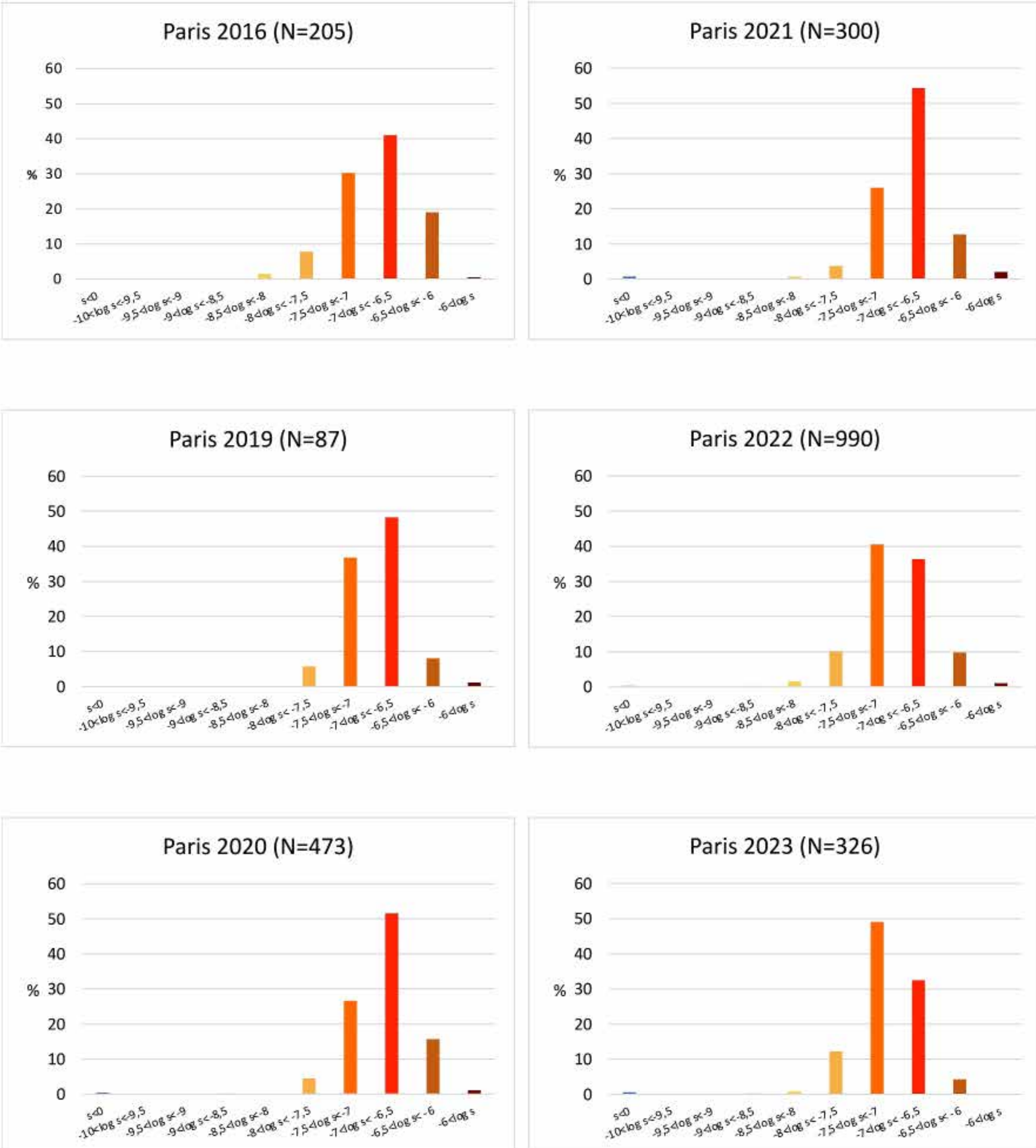

Figure 5. Distribution of susceptibility values measured for each sampling campaign. Bins and color scales are the same are those used on the maps of Figure 4. The color scales from dark green to gray correspond to log (susceptibility); the blue color scale corresponds to negative susceptibility values.

The samples from the 2020 campaign were all measured at IPGP. The average susceptibility value for all 473 samples is 0.21×10^{-6} m^3/kg (ls: −6.7) with data ranging from negative values to 4.29×10^{-6} m^3/kg (ls: −5.4). The data obtained for the trees along the Seine can be compared with data from the previous years (Figure 4c). High values are again observed for the trees along the Pompidou Expressway, as well as for the area along the Seine near the Jardin des Tuileries, where the values are higher than in 2019. In comparison, the new transects along the roads sampled during this campaign rarely showed such high susceptibilities. Other newly identified areas with high values are localized along the Quai de Bercy near the main bus station in Paris, and the intersection of Rue de Réaumur—Rue de Sébastopol, a busy and often congested intersection. This could explain the increase of the average susceptibility value as also seen in the histogram distribution (Figure 5c).

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Table 1
Median, Mean and Standard Deviations for All Susceptibility Values for Each Sampling Year

	Median	Mean	Std deviation	
2016	0.1334	0.19565083	0.188775418	s (10^{-6} m^3/kg)
	−6.87484417	−6.7085183	−6.72405456	log s
2019	0.113	0.17466837	0.192987202	s (10^{-6} m^3/kg)
	−6.94692156	−6.7577857	−6.71447149	log s
2020	0.143269916	0.20620154	0.277985707	s (10^{-6} m^3/kg)
	−6.84384499	−6.6857081	−6.55597753	log s
2021	0.118053	0.16546565	0.176416773	s (10^{-6} m^3/kg)
	−6.92792297	−6.7812921	−6.75346013	log s
2022	0.094920292	0.15582978	0.213761582	s (10^{-6} m^3/kg)
	−7.02264093	−6.8073495	−6.67007034	log s
2023	0.077280385	0.10571452	0.088384582	s (10^{-6} m^3/kg)
	−7.11193072	−6.9758654	−7.05362349	log s

Note. Log values are also given for the median and mean values for comparison with the scale of Figure 4.

While the Seine River transect was sampled by the scientific team in 2021, the distribution of samples in the rest of Paris was much more random, as volunteers were not told where to collect samples. Plane trees are also unevenly distributed across the city, with some avenues being richer in plane trees than others. As a consequence, some areas were over-represented while others were not sampled at all (Figure 4d). The north-east of Paris was well sampled, in particular Rue des Pyrénées, thanks to the participation of an active citizen association called "Respirons mieux dans la ville" ("*Breathing easier in the city*"), a project financed by the City of Paris' participatory budget, which helped to raise awareness in this area and mobilized a number of participants. Values ranged up to 1.78×10^{-6} m^3/kg (ls: −5.7); the average value for 2021 is 0.17×10^{-6} m^3/kg (ls: −6.8). It is important to remember that severe movement restrictions related to the COVID-19 pandemic took place in 2020. In France, a strict lock-down was put in place during 2 months and a more lenient one during 1.5 months, as well as curfew periods. Consequently, the 2021 samples correspond to plane trees in a confined environment at different times, with less circulation. When compared with the 2020 map (samples before COVID—not affected by circulation restrictions—the sampling took place just before the COVID crisis), we notice a general decrease of mean magnetic susceptibility in 2021, including along the Pompidou expressway (Figure 8). However, the susceptibility values of the area along the Quai des Tuileries remain high.

The extension of the Ecorc'Air project in 2022, with increased support from the City of Paris, has enabled us to cover more areas. We obtained samples from the Seine transect as in previous years, but also some detailed measurements along new transects (Figure 4e). The average susceptibility is 0.16×10^{-6} m^3/kg (ls: −6.8) and values range up to 3.2×10^{-6} m^3/kg (ls: −5.5). For most of the areas already sampled in the 2021, we see a general decrease in magnetic susceptibility, for example, along the Rue des Pyrénées and the Pompidou expressway. This general decrease is also observable in the histogram distribution which is slightly shifted toward lower values (Figure 5e).

Finally, the map for 2023 is very different as we only relied on the sampling strategy of the volunteers. The long transects that were previously sampled by the scientific team are absent; instead, the sampling points are much more dispersed. The north-east of Paris (Rue des Pyrénées) is always well sampled (as in 2021 and 2022), thanks to the active participation of the members of "Respirons mieux dans la ville" (Figure 4f). The mean value of 0.11×10^{-6} m^3/kg (ls: −6.9) for the whole city probably reflects the lack of data from long transects along busy roads, which the scientific team has been targeting in recent years (e.g., Boulevard Saint Germain, Seine transect). This causes a shift of the susceptibility histogram toward lower values (Figure 5f), which was also observed, at a lesser degree, in 2021 and 2022.

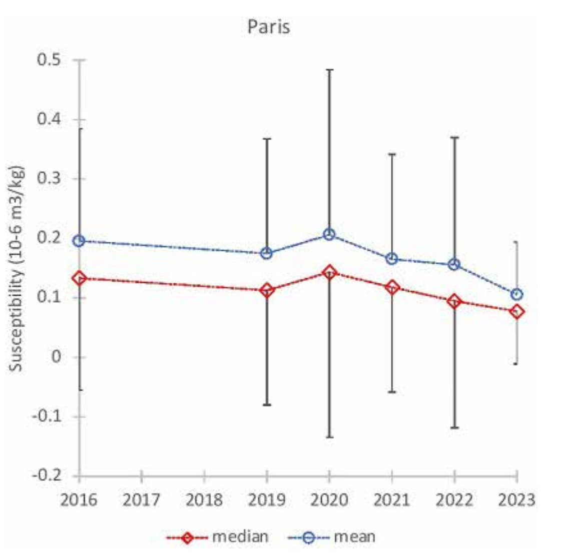

Figure 6. Median (red dotted line) and mean (blue dotted line) susceptibility values for each sampling year. Error bars are the standard deviation values.

4.3. Participation Results and Survey of the People Involved

Since its launch in 2020 with the support of the City of Paris since 2021, the Ecorc'Air project has benefited from the participation of volunteers to significantly increase the number of samples collected in Paris, but also to a lesser extent in neighboring municipalities, and in other major European cities, especially in 2023 (Figure 2). We received samples from individuals, but also through local environmental associations. Schoolchildren also took part, as well as youth organizations, such as Scouts.

The survey conducted by the five PSL students allows us to answer some questions about the involvement of volunteers in Ecorc'Air. First, the reasons for participation were asked. The simplicity of the protocol seems to be a source of motivation to participate, as Sophie (for reasons of anonymity, the

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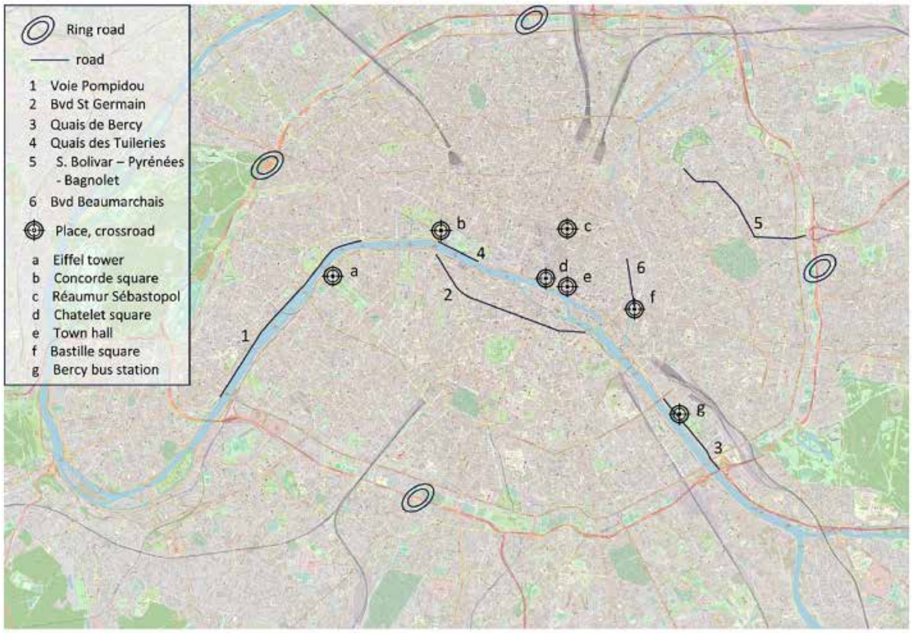

Figure 7. Localization of points of interest mentioned in this study.

first names of respondents have been changed), an employee of Nanterre town hall, puts it: “It's the simplest of all the [protocols] we use.” For individual volunteers, the appeal of science and the participatory approach seems to be more attractive than the issue of air quality per se. The same is true for the volunteers involved in the Lichens GO program. The volunteers interviewed in 2017 were more interested in learning about lichens than in air quality (Abensour et al., 2020). On the contrary, the volunteers involved as part of a collective of local residents are concerned about the quality of their living environment, as the president of the association “Ensemble vivons Versailles” (*Living together at Versailles*) explained to the newspaper “Le Parisien”: “What interests us is to follow the evolution of air pollution on this road axis year after year.” Ecorc’Air is then seen as a means of collecting reliable data that can be used to alert the authorities if necessary.

The survey also highlighted a number of potential limitations to volunteer involvement. The first was the danger of collecting near road traffic, as Manon put it: “I've always been afraid of being hit by a car (laughs),” and Franck

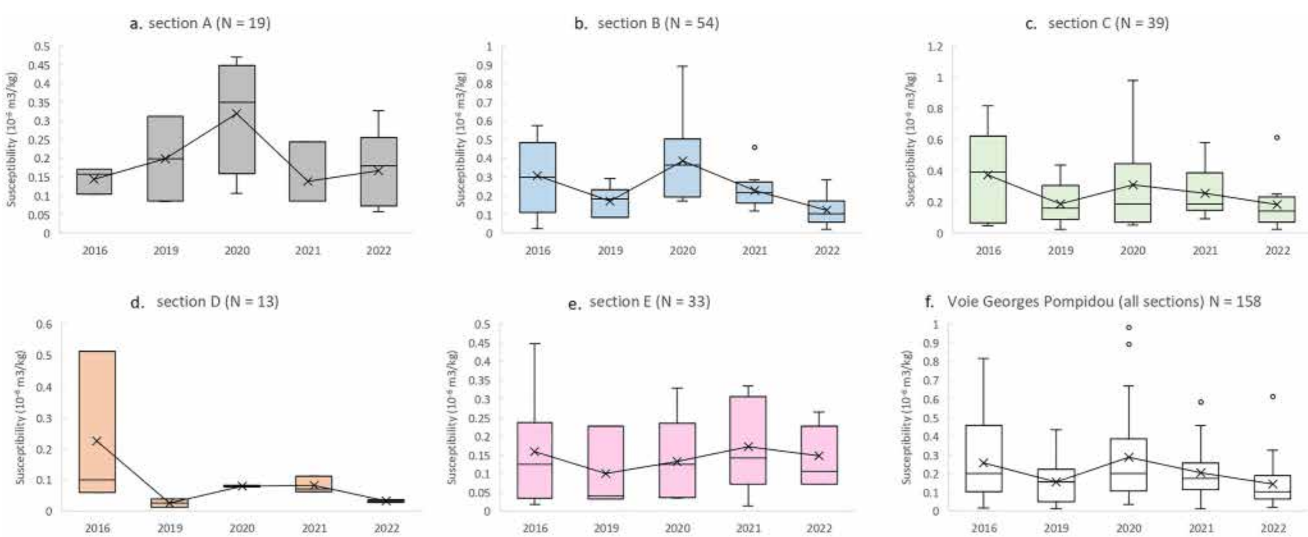

Figure 8. a–e: variation of susceptibility values per section along the Pompidou Highway as a function of sampling year. f: variation of the average of the sections.

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noted that "with children it's even more of a problem because you're responsible for their health and safety. Thus, involving children in an activity where you're on the side of the road is something that holds me back a little from Ecorc'Air." Manon also points out a second limitation: the potentially long time between the collection of the samples and the return of the analysis results to the volunteers, who may have moved on to other things and may have lost the motivation for long-term involvement: "But from the point of view of public awareness, it depends on whether they get frequent feedback or not."

Although the volunteers interviewed did not seem to be always involved in Ecorc'Air primarily because of an interest in air quality, the survey did allow us to study their perceptions of air quality. For some of them, like Jude or Lea, two of the girl scouts, pollution seems invisible: "I've lived in Paris since I was a small child, so I don't notice much difference, it's always the same," "I don't have a problem with air pollution." Others, like Sophie, say that they only feel the pollution peaks: "So I don't feel the pollution, except from time to time, when there's a big spike, I have a headache." And finally, some are really bothered by pollution, like Anne, one of the Nanterre town employees: "I came to Paris in 1999. The first year, bam! first asthma attack," or Fanny, one of the high school students: "Sometimes I cough when I come to Paris." Ultimately, these results undoubtedly reflect a different sensitivity to pollution from one person to another. However, it seems that people who have grown up outside a large city or who have been sheltered from pollution are more sensitive to it, as Manon explains: "I noticed that I was really breathing badly all day long, and it's sad to say, but after a year in such an environment, I had adapted."

Municipalities see citizen science as a way to connect with their citizens on environmental issues where decisions need to be made in consultation with local residents, as Anne points out: "This dynamic between municipal public policy on the one hand and the [residents] on the other, through participation, I think is quite a positive dynamic." Citizen science is also seen as a source of data for municipalities that do not have an official air quality measurement facility, as a deputy from Yvelines (where the city of Versailles is located) explained in the article in Le Parisien: "As far as I know, there is no official measurement of fine particles in Versailles."

5. Discussion

Thanks to the large data set, several particular key questions can be addressed. We have chosen to focus on three aspects: the temporal evolution of the susceptibility values along the Seine River, the spatial differences between sections of a road and the identification of particular pollution hotspots. The question of the correlation of the results with car traffic is complex and will be addressed in a companion study.

5.1. Identification of Pollution Hotspots

Thanks to our six sets of measurements, it is possible to identify recurrent problematic areas where susceptibility values are consistently high. Such a visual representation is the main advantage of the mapping of the results. Some of these areas (localized on Figure 7) are the following:

- The right bank quays between the Tuileries garden and the Chatelet square. This road is a 2- or 3-lane road with frequent traffic lights and is often congested.
- The Bercy Quays (left bank quays), sampled in 2020 and 2022, show high susceptibility values. There are three lanes of heavy traffic along these quays as well as the access to the main bus station.
- Boulevard Beaumarchais (north of Bastille Square), sampled in 2020 and 2023, shows values higher than on other main roads of the same neighborhood. There are also three lanes of heavy traffic and it is often congested.
- We also notice a clear effect of the Boulevard Periphérique, the main ring road. High values can be seen nearby, in the south-west part of the city (sampled in 2016, 2019, 2021, and 2022), but also in the east (sampled in 2021 and more extensively in 2023) and in the south-west of Paris (sampled in 2020). These high levels are more likely to be caused by the heavy congestion and traffic at junctions leading to the ring road itself.

On the opposite side of the spectrum, the few values that we have measured in samples from parks and green spaces, several tens of meters away from any traffic lanes, are extremely low (several orders of magnitude lower than the highest observed values). Some rare samples have negative values ($s < 0$, in blue—2022 and 2023, Figure 4), characteristic of non-contaminated samples. This tends to confirm that the magnetic signal is mainly caused by vehicle traffic and that the background signal and some other sources of pollution are negligible.

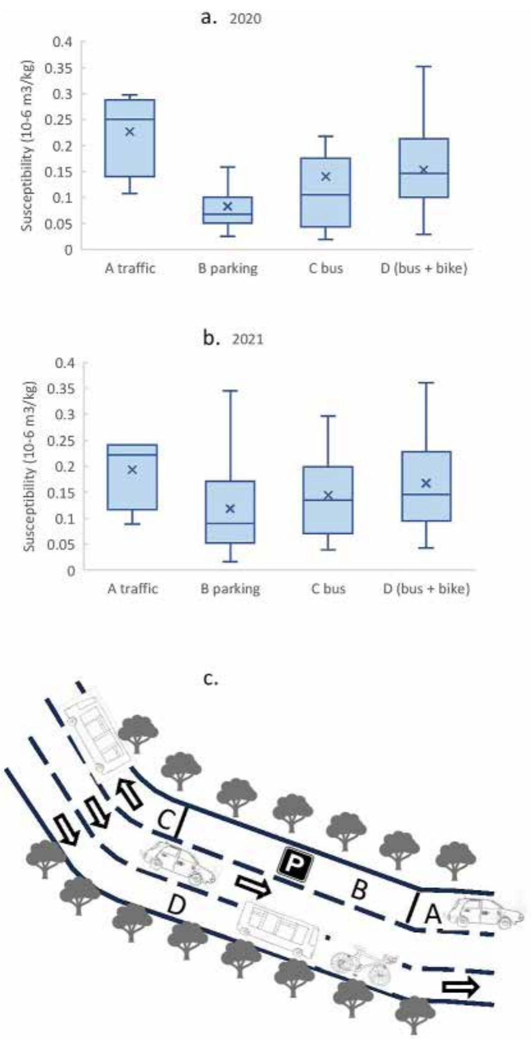

Figure 9. Average of susceptibility values along Bd. St Germain for years 2020 (a) and 2021 (b) depending on the kind of vehicles circulating on the lane the closest of the trees. (c) Sketch of the organization of traffic lanes of the Boulevard showing the four configurations A, B, C, D.

5.2. Comparison Over Four Years of Values Along the Pompidou Expressway

The Pompidou Expressway is one of the sites regularly sampled during the entire study period. This allows us to make a more specific analysis of the changes in susceptibility over the years. The transect length (about 3 km) was divided into five sections where there is no crossing, so that the flow of vehicles is similar on each section. The susceptibility values were then averaged over each section, with approximately 5–6 sampling points per section. The variation of susceptibility with time shows some similarities for all sections (Figures 8a–8e). There is a general decrease between 2016 and 2019, except for section A. This could be due to the replacement of one of the two original traffic lanes with a bidirectional bicycle lane created in 2018. However, we cannot overlook the fact that this overall phenomenon, also observed for the average values for Paris, that may be partially attributed to a change in the measuring device between 2016 and 2019. Interestingly, this change did not affect section A, where there was an increase in susceptibility. There is then an increase in susceptibility between 2019 and 2020, followed by a decrease between 2020 and 2021, which could be linked to the periods of lock-down associated with COVID (2 months of very little car traffic). The decrease, or at least some stabilization, persists for all sections except section A between 2021 and 2022. Despite the large scatter of values within each section, this also shows that meaningful and consistent trends can be extracted from our measurements, though a comparison with car flow will be needed to confirm the causes of these trends. The average of the results for the five sections shows the general trend for the Pompidou Expressway: a decrease of susceptibility in 2019, followed by an increase in 2020, and a steady decrease thereafter (Figure 8f). It is important to emphasize that the changes in susceptibility since 2019 cannot be attributed to the change in measuring equipment.

5.3. Differences Between Sections of the Same Street Depending of Cycle/Bus Lane/Parking Lane/Car Lane

During the 2020 and 2021 sampling campaigns, we extensively sampled trees on both sides of Boulevard St Germain, a major west-east road in the center of Paris. It is mostly one-way, 3 km long, and consists of three lanes: the right lane is a shared bus-bicycle-taxi lane, the middle lane is the general car lane, and the right-side is either another car lane, a bus-taxi lane in the opposite direction, or used for car parking (Figure 9a).

The data from this avenue were classified into four categories depending on the type of traffic on the lane closest to the sampled trees. Whisker plots (Figures 9b and 9c) for data from either 2020 or 2021 show that the barks sampled from trees close to the general car lane (A) have the highest values, followed by those from trees close to the bus-taxi (C) lane and to the shared bus-bicycle-taxi lane (D). Finally, the lowest values are found for the trees that are bordered by the parked cars (B).

To test whether the differences in susceptibility values between these four categories are statistically significant, a 2-way analysis of variance was applied, with magnetic susceptibility as the dependent variable and traffic type (A, B, C, or D, as previously defined) as independent variables. Susceptibility values were log-transformed prior to the statistical analysis to meet residual normality and homoscedasticity assumptions. Multiple pairwise comparisons were carried out using Tukey honestly significant difference tests. Statistical analysis was performed using the software R version 4.3.3. The results from the combined 2020–2021 data set show (Figure S3 in Supporting Information S1) that values along the parked car areas (B category) are significantly different from values at bus-bicycle-taxi lane (D category), at general car lane (A category) and at bus-taxi lane (C category) all combined. However, values from the three latter categories are not significantly different from each other.

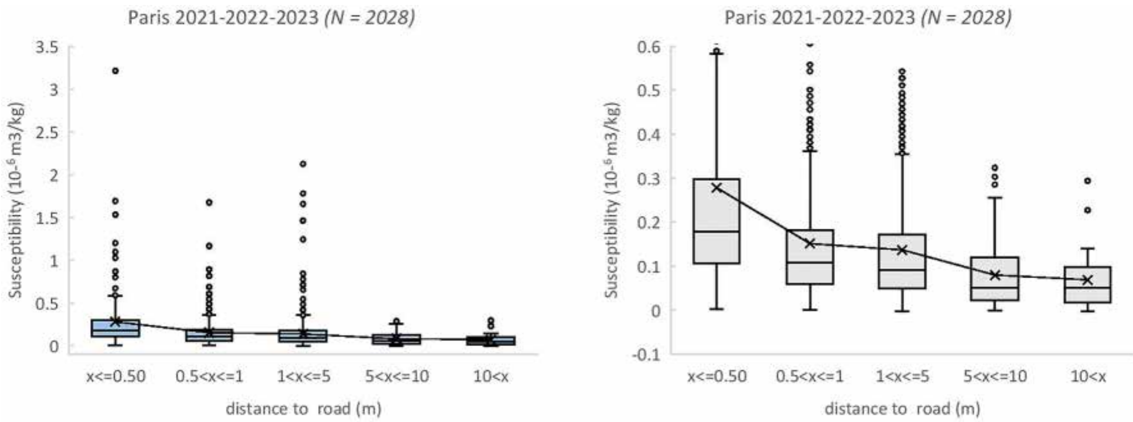

Figure 10. Average of susceptibility values from 2021 to 2022–2023 sampling campaigns per categories of distance of the sampled tree to the road as informed on the individual sampling sheet. left: all data; right: zoom on the smallest values.

These results are consistent with two possible effects. First, it is very likely that the parked cars have a shielding effect, preventing the PM emitted from the vehicles from being deposited on the trees planted on the opposite side of the traffic lane. In addition, these trees are further away from traffic than if there were no parked cars. This could also explain the lower susceptibility values (less PM reaches these trees—see Section 4 below) (Figure 10). Our results show that cyclists circulating in the lane shared with buses and taxis (D) are exposed to significant PM. Separated cycle lanes would therefore offer cyclists better protection from PM than the shared lanes with buses and taxis that are still common in Paris and many large cities.

5.4. The Influence of the Distance From the Road

One of the metadata that is systematically provided with each bark sample is an estimate of the distance of the tree from the road. Most trees are less than 10 m away from the road. We have grouped the susceptibility values into five representative distance categories, for the years 2021, 2022, and 2023. There is a large spread (Figure 10) because samples from each location in our Paris database are included in this plot. Nevertheless, we can assume that effect of the different locations would be canceled out, as the database is quite large (several hundred points per year, Figure 1, and a total of 3,375 trees). We find that for the three data sets, the average susceptibility values decrease as the distance from the road increases (Figure 10 and Figure S2 in Supporting Information S1). When the three data sets are combined together, a strong decrease in susceptibility is observed when comparing values in the range from 0 to 0.5 m with those in the range 0.5–1 m (Figure 10). The decrease is less pronounced as the distance from the road increases. This is consistent with other studies of the magnetic signal from tree leaves and filters sampled at various distances from roads in urban areas, although they are rarely carried out on a large number of data (e.g., Maher et al., 2008; Matzka & Maher, 1999; Moreno et al., 2003). This relatively rapid decrease also confirms that the magnetic measurements mostly detect PM in the large particle size range and not the finest PM, such as $PM_{0.1}$, which can travel further from the source (Muxworthy et al., 2022). This magnetic PM fraction of larger grain size due to circulating motor vehicles is most likely due to brake dust (e.g., Gonet et al., 2021; Sagnotti et al., 2009; Winkler et al., 2020).

5.5. Involvement of Volunteers

The survey we carried out allows us to better understand the sources of motivation for volunteers and the potential limits to their involvement in Ecorc'Air. Based on these results, we can improve our interaction with volunteers in order to better meet their expectations and maintain or increase their involvement, as well as reach out to new volunteers. Our survey shows that some individual volunteers are involved not because they are interested in air quality, but rather because they are attracted by the scientific volunteering. The question is how to retain these volunteers in the long term: after a while, they may want to do science on other topics and switch to volunteering for another citizen science project. Moreover, some of the volunteers interviewed in 2021 are no longer participating. Finally, the involvement of groups of residents concerned about the environmental and air quality of their neighborhood should be more massive and long-term. This hypothesis seems to be confirmed with the "Ensemble

Vivons Versailles" and "Respirons mieux dans la ville" associations, which collect numerous samples each year. Furthermore, collaboration with these groups brings new questions for the project, particularly in documenting the health impact due to PM exposure. Ecorc'Air's communication efforts should therefore be directed toward these local groups. Collaboration with local authorities can help to target these groups.

The main limitation to participation identified by the survey, and which we can act upon, is our sample analysis time, and therefore our return time to the volunteers with a measurement made on their samples. We are fully aware of this limitation and each year we do our best to carry out these analyses as quickly as possible, in particular with the help of several interns. Nevertheless, the analysis time is long and we are sometimes overwhelmed by the large number of samples. However, in order to make the interaction with volunteers more regular and dynamic, we are currently exploring two avenues. The first is to develop a smartphone application that would geolocate sample collection in real time. This would allow volunteers to see directly where samples have already been taken and where samples are missing. This application will also make it possible to consult the measured values once the analyses have been carried out. The magnetic susceptibility maps for various towns (Paris, Versailles, Lyon, Berlin, …) are accessible online (https://www.ipgp.fr/la-recherche/projets-de-recherche/projet-ecorcair/). To make the consultation of the results more dynamic, we are also working on an interactive map that will allow volunteers to visualize the data collected by Ecorc'Air since 2016. We are also considering the purchase of portable susceptibility meters that could be lent out to groups, such as associations, communities or schools. This would enable volunteers to carry out their own measurements after a short training session. This has two advantages: first, the volunteers will not have to wait for the results of the analyses, but more importantly, they will be able to understand a live measurement process.

6. Conclusion

In this paper, we presented Ecorc'Air, a Citizen Science project running since 2020 in Paris. The following conclusions can be drawn from our results:

1. Elemental analysis confirmed that the magnetic susceptibility of the tree bark is a suitable proxy indicator for metallic PM of vehicular origin in urban environments.
2. There is a growing interest and participation of city dwellers, and particularly those who are involved in local association, to take action in favor of environmental research, as well as of municipalities to offer some support, at least in terms of logistics and communication.
3. Several particular areas of consistently high susceptibility values over time have been identified.
4. Two effects have been highlighted by our measurements: the rapid decrease in susceptibility values as the distance between the sampled tree and the road increases, and the screening effect of the parked vehicles on people walking on the pavement. Although these effects are quite intuitive, it is important to have data to support them.
5. Finally, we were able to show some trends in susceptibility variation over time along the Pompidou Expressway, one of the main roads in Paris. At the scale of a large city such as Paris, such sampling and measurements can help to measure the effects of local urban planning changes.

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Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The data used for analysis in the study are available at IPGP repository via https://doi.org/10.18715/IPGP.2024.m0b84bco with Licence Ouverte/Open Licence 2.0.

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