



Who Breathes What?

A Spatial Exploration of Air Quality Exposure and Socio-Economic Inequalities in Belgium

by

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Abstract

This research paper explores the question “*who breathes what?*” by examining the intersection of air quality exposure and socio-economic inequalities in Belgium. Drawing on a data-driven approach, it asks whether the burden of air pollution falls disproportionately on socio-economically disadvantaged populations, and what spatial patterns emerge from such an analysis. The study first critically engages with the air quality data produced by IRCELINE, the Belgian federal scientific institution responsible for air pollution monitoring, assessing how these data are produced, what spatial resolution they offer, and what limitations they carry for environmental justice research. Using four key pollutants, PM_{2.5}, PM₁₀, NO₂ and Black Carbon, the study maps spatial distribution among different Belgian municipalities in concordance with socio-economic indicators. To operationalize the relationship between pollution exposure and socio-economic conditions, three municipal-level indicators are mobilized: median annual gross income (2023), average real estate prices for houses with two or three street-facing sides (2025) and the administrative risk of poverty (2023). Applying the Pearson correlation coefficient, the study aims to investigate whether disparities in air pollution exposure systematically coincide with socio-economic disadvantage.

Keywords: environmental inequalities, air pollution, socio-economic disparities, differentiated exposure

Introduction

Air pollution is the largest environmental risk to public health in the world today (World Health Organization). Following the Health Effects Institute (HEI) report, air pollution caused 8,1 million deaths worldwide in 2021. Written with UNICEF, the report also reveals that children before five years old are particularly vulnerable, with health effects such as premature birth, low birth weight, asthma, and lung diseases (CCAC, 2024). Air pollution, defined as the contamination of the indoor or outdoor environment (by chemical, physical or biological agents) is one of the main causes of death, increasing year by year due to climate change. Although air pollution affects the poorest and developing countries, the European Union also reports concerning statistics. In fact, it remains the largest environmental health risk in Europe, and most European city dwellers are exposed to unsafe levels of air pollution (EEA, 2026). In 2023, 182,000 deaths were caused from exposure to fine particulate matter; 34,000 from exposure to nitrogen dioxide, and 63,000 from exposure to ozone (EEA, 2025).

To reduce by half premature deaths caused by exposure to fine particulate matter, the EU has stepped up its efforts and implemented directives to reduce air pollution. Ambitious climate targets set out in the European Green Deal following the green wave in 2018, the number of deaths in the EU attributable to PM_{2.5} fell by 57% between 2005 and 2023 within the Zero Pollution Action Plan for 2030, initiated by the European Commission.

It seems that not everyone is on an equal footing when it comes to the challenges associated with climate change. According to the EEA, “society’s most vulnerable are more susceptible to air pollution impacts”. In fact, the question of environmental inequalities have been well-documented in the academic debate since the 1990s. This research paper aims to test and apply this statement to the case of Belgium. It is an interesting country in terms of spatial analysis as it is divided by three main parts: Wallonia, Flanders and Brussels-Capital Region, each one having its own characteristics. Socio-economic categories, standard of living and quality of life vary a lot among those three regions. According to the IRCELINE 2024 Annual Report, air quality in Belgium has gradually improved over the last three decades. Despite this constant improvement, the entire population remains exposed to concentrations higher than the values recommended by the World Health Organization (WHO) for PM₁₀, PM_{2.5}, NO₂ and the ozone in 2024.

Despite growing policy attention to this issue, the spatial relationship between air pollution and socio-economic inequalities remains underexplored in the Belgian context. This paper answers the following research question: **How do spatial segregation and socio-economic indicators shape differentiated exposure to air pollution in Belgium?**

This research paper addresses this gap through a two step research process. After a broad and comprehensive literature review, the first part delves into IRCELINE's spatial air quality data to critically examine how air pollution data is produced in Belgium, as well as the limits arising from its methodology. The second part will explore the relationship between air pollution exposure and socio-economic inequalities through descriptive statistics and spatial analysis methods. Through maps, trend analysis and exposure indicators (PM10, PM2.5, Black Carbon and NO2), the goal is to highlight differential exposure and environmental inequalities in Belgium.

Literature Review

This literature review aims to provide a comprehensive overview of previous research done on environmental inequalities, and to have a particular look at air pollution within the context of Belgium. It will explore established consensus, emerging trends, and gaps in the existing literature. The paper encompasses a corpus of texts dealing with environmental inequality as a complex notion. When possible, it identifies the main challenges of air pollution and differentiated exposure based on socio-economic factors in Belgium. Finally, the last section fills the gap in the literature by mixing both sections and sets out the issues that will be addressed in the methodology and the empirical sections.

1. “No One Left Behind”: Environmental Inequalities Shaping Climate Change Realities?

Following the European Environmental Agency (EEA), environmental inequalities occur when “communities with lower levels of income and education are often more impacted by air, water and noise pollution, as well as climate change”. Among the most vulnerable groups affected by environmental inequalities, we find the elderly, children, and low-income populations. Beyond inequalities and a sense of injustice, they are more likely to be affected or worsened by environmental hazards. The social aspect and the notion of environmental justice need to be at the heart of climate change policies, as it is enshrined in the EU Green Deal foundational

principle of “No one left behind”. Indeed, the existing researches and theories about environmental inequalities agree on this dominant and initial consensus: good health and quality of life are not equally distributed.

Defining Environmental Inequalities: History, Roots and Beyond

In the late 1970s and the 1980s, a series of environmental justice movements arose in the United States which led to the academic development of the “environmental racism” concept. Environmental justice is rooted in community activism, as its claims found their roots in the *toxics* movements hand in hand with the rise of civil rights mobilisations (Purdy, 2018). At this time, the US faced a toxic waste crisis where a lot of sites were contaminated by hazardous chemicals. Toxic waste sites and polluting industries were disproportionately located in low-income and people of color (POC) communities. The 1982 Warren County protest can be defined as the birth of environmental justice in the US: it “bridged [...] the environmental movement and the civil rights movement by explicitly linking environmental degradation to racial injustice” (Wang, 2025, p. 11). In this article titled “*Warren County and the Birth of Environmental Justice: From Local Protest to a National Movement*”, the author highlights how this protest gave voice to marginalized communities from environmental decision-making and confronted with a disproportionate burden of toxic pollution.

These events led scholars to search and extend the scope of environmental justice to environmental inequalities. Following Shao *et. al* (2022), environmental inequality puts an emphasis on the differences in outcomes and focuses on the unbalanced environmental burden on specific groups. As Shao explains “environmental risks among groups are closely related to their race, color, national origin and income, and the minority groups bear more serious pollution exposure risks.” (2022, p. 3136). Some scholars add other components to this definition, stating for instance that environmental inequality also focuses on “the intersection between environmental quality and social hierarchies” (Pellow, 2000, p. 582). The question of inequality addresses structural questions such as the unequal distribution of power and resources in society, translated into environmental “burdens”. This analysis could be closely linked to a Marxist interpretation, in which social structures and hierarchies are at the heart of environmental inequalities. In this regard, a range of authors consider environmental inequality as inherent in political economy, and that general environmental justice research has excluded the question of social class in environmental research (Szasz & Meuser, 1997 in Simon, 2000). Scholars highlight the differentiated exposure (*see section 2.1*) between the lower and working class, and upper class. On the one hand, the most vulnerable communities are the most exposed to polluting industries,

waste, polluted air, while on the other hand, the upper and rich class enjoy healthier environments with green neighborhoods and less polluted areas. Reflecting on the structural roots and existing social stratification beyond race, origin, and other intersectional factors is essential to understanding the real challenges at play in the manifestation of environmental inequalities.

To conclude this first section, a broad and complete definition of environmental justice and inequalities cannot be done without mentioning the seminal works of Robert Bullard, the founding director of the Environmental Justice Resource Center at Clark Atlanta University. His 1996 work *Environmental justice: It's more than waste facility siting*, states the principle that “all people and communities are entitled to equal protection of environmental and public health laws and regulation”. (Bullard, 1996, p. 493). His political and legal framing reinforces the substance of the environmental (in)justice definition, whereas many scholars stopped at academic definitional boundaries. In fact, a range of authors highlights the need to incorporate notions of environmental injustice and inequalities into policy agendas and constitutions. His other most famous book *Dumping in Dixie: Race, Class and Environmental Quality* (Hamilton & Bullard, 1991) puts forward the notion of environmental *equity*, that is the development and enforcement of environmental policies and laws preventing any community from bearing the costs of a disproportionate share of pollution and its associated risks.

The “Spatial Extent” of Environmental Inequalities

The spatial dimension is a key component within the study of environmental inequalities as it sets the challenges related to the scale and extent. A branch of authors have searched the impact of spatial segregation and the concept of “sacrifice zones” which both influence how people face differently the cost of climate change. As this paper uses air pollution spatial analysis and related environmental inequalities, it is essential to acknowledge the issue of spatial segregation within the context of environmental inequalities. Following Tivadar & Schaeffer (2026) in their article *From spatial segregation to environmental inequalities: Mathematical and empirical evidence*, spatial segregation can be defined as the “separation of different population groups in space” (p. 2). The authors explain that environmental inequalities are structured around the spatial dimension closely linked to the spatial segregation of different social groups: “if two groups had identical spatial distributions, there would be no spatial environmental inequalities between them”. This mathematical study shows, through the use of dissimilarity-based and Gini-based indices, that spatial environmental inequalities between social groups are bounded by the degree of spatial segregation. Following this logic, poor and minority neighborhoods are

disproportionately affected by environmental hazards.

To further support this argument, several environmental justice researchers have dismissed the concept of “sacrifice zones” (Juskus, 2023; Lerner, 2010), defining them as “semi-industrial areas, largely populated by African Americans, Latinos, Native Americans, and low-income whites, where [...] racial and economic discrimination persists”. As it is highlighted, the notion of social and economic discrimination is central to its definition. Two hypotheses could explain why spatial segregation happens: polluting industries tend to locate in already disadvantaged areas (*sitting hypothesis*); vulnerable populations migrate to these areas because of the low cost of housing (*move-in hypothesis*) (Been, 1994).

While there appears to be a broad consensus regarding the spatial dimension of environmental inequalities, some researchers have sought how results vary across spatial scales in order to nuance these observations. In this regard, there is no single spatial truth about environmental inequalities, and some scholars call for a scale-dependent research (Carvalho et al., 2022). Their study analyzes the statistical relationships between socio-economic disparities and environmental vulnerability at several spatial scales (i.e. metropolitan areas, municipalities, and boroughs). As previously mentioned, it shows that the most vulnerable populations tend to be more exposed and affected by environmental hazards at the metropolitan areas and municipal levels. However, at a more local scale, some rich elite groups are also exposed to significant risks, as they often settle in remote and privileged areas prone to natural disasters. Ultimately, the authors emphasize the unequal distribution of protective infrastructures and the disparities in the level of protection between poor and wealthy populations.

In the context of air pollution, spatial segregation plays a crucial role in shaping differentiated exposure patterns according to residential location. This relationship is further explored in the following section.

2. Breathing Inequality: Air Pollution and Its Unequal Burdens

According to the World Health Organization, ambient air pollution and household air pollution are associated with 6,7 million premature deaths annually, 89% of which occur in low and middle income countries, especially in the WHO South-East Asia and Western Pacific Regions (WHO, 2024). Very recent studies from the World Stroke Organization have shown that air pollution may constitute a major risk factor for stroke (Saad et al., 2026). Beyond these global figures, the literature on air pollution has been growing examining air pollution through the lens of social inequality highlighting a key notion: differentiated exposure. This second section will

focus on the relationship between air pollution and socio-economic inequalities at the European level before narrowing the focus to the case of Belgium.

Air Pollution and Differentiated Exposure at the European level

Air pollution exposure has been strictly studied in the environmental justice field of research, particularly the concept of differential (or differentiated) exposure. Most authors agree on the same point: higher deprivation indices and low economic position are usually linked with higher levels of pollutants (Fairbun, 2019; Kruize et al., 2014), especially particulate matter (PM_{2.5}, PM₁₀) and nitrogen oxides (NO₂, NO_x). In the academic article *Social inequalities resulting from health risks related to ambient air quality – A European review* (Deguen, 2010), the author gives a clear definition of differential exposure: “among the general population, disadvantaged groups are recognized as being more often exposed to sources of pollution” (p. 27). They also highlight one other key concept of “differential susceptibility”: disadvantaged groups are not only more exposed to air pollution, but also more likely to suffer severe health effects from that exposure, due to pre-existing vulnerabilities (e.g. poor health conditions, limited healthcare access, chronic stress). The paper states that “populations with poor-economical status live in areas with lower ambient air quality than richer ones” (p. 27).

A lot of research focused on air pollution exposure at the European level. Following Fairbun (2019) there is a growing attention to air quality, notably through the different major policies such as the Ambient Air Quality Directive, that is implemented by all Member States but also encourages them to improve air quality at a local and regional level. Although the air quality guidelines fixed by the WHO are not met, air pollution has been declining since 1990. In Europe, the main pollutant is emissions of nitrogen oxides (NO_x), that derive mostly from road transport in urban areas, particularly diesel vehicles (Gelotte, 2017).

There is also a strong consensus on the significant disparities remaining between East and West in Europe regarding air quality, where Eastern European citizens continue to breathe the most polluted air and suffer the highest air pollution health burden (Andersen, 2025). One main issue is the lack of data and access to air pollution exposure information in Eastern Europe, a gap particularly pronounced in the most deprived areas of each country, where evidence-based solutions remain scarce.

To conclude, it is also interesting to understand the factors that influence the deprivation of vulnerable populations the most. Henninger & Smith (2024) have found in their article *Beyond the haze: decomposing the effect of economic inequality on global air quality from 2000 to 2020*, that the level

of economic development (GDP per capita) and the quality of democratic institutions have much more impact than economic inequality alone. Overall, several authors underline the need for more intersectional research on air pollution crossing different social indicators as this paper aims to do.

Unequal Air Pollution Exposure in Belgium

Although ambient air quality in Belgium is generally improving, a considerable part of the population is still breathing contaminated air. Few scholars have analyzed the case of Belgium, and these are generally spatial studies focused on one or more cities for comparative purposes. There is little, if any, nationwide analysis of air pollution, hence the relevance of this paper.

The literature about Belgium is often divided between Flanders (Dutch speaking part of the country), Wallonia (French-speaking side) and Brussels (cosmopolitan and international). An interesting study about socioeconomic inequalities and ambient air pollution exposure in school-aged children stresses two relevant factors to take into account: education and income. It also concludes that children from parents with a low socioeconomic status are more likely to be exposed to contaminated air ([Mustansar et al., 2025](#)). Scholars highlight how various dimensions of social inequality interact to shape patterns of air pollution exposure and health disparities. In parallel, a geospatial environmental justice analysis in Ghent also emphasizes the need to include all kinds of socio-demographic dimensions in environmental impact exposure ([Verbeek, 2019](#)). His research shows that “people in more deprived neighborhoods with lower incomes, more unemployment, a higher percentage of foreign origin people, a high percentage of rental houses and a higher residential mobility, were more exposed to air pollution” (p. 9). Although this study focuses on Ghent, it provides a foundation for us to build upon and allow us to continue our research on a larger scale. Finally, other researchers have focused on differentiated air pollution through the development of urban policies. Low emission zones (LEZ) are one of the solutions to improve air quality within cities, and they have shown their efficiency in Belgium ([Bruyneel et al., 2025](#)). In fact, in Brussels for instance, NO₂ concentrations reduced from 29.44 µg/m³ in 2017, the year before the introduction of the LEZ, to 18.53 µg/m³ in 2022. As well as the other Belgian studies, scholars insist on the need of social component in urban policies to improve air quality. Again, the study concludes that the most deprived neighbourhoods bear the heaviest burden of air pollution, however, they benefitted most from the implementation of the LEZ. On the same level, greening urban spaces seems like another solution. Following [Ducol et al. \(2025\)](#), there is an unequal distribution of urban features contributing to the spatial dimension of

socio-environmental inequalities. For example, in Brussels, working-class neighborhoods in the city center experience higher levels of air pollution. The authors argue that the “ecological double penalty” (Comby & Malier, 2021) is not only related to air quality but also to the fact that the most vulnerable groups have more limited access to urban and environmental services in Brussels. In conclusion, while there are not many studies on this topic in Belgium, they all reach the same conclusion: the most disadvantaged groups in Belgium bear the heaviest cost of the ecological debt.

3. Filling the Gap: Toward a National Multi-Factor Analysis

To mix up the first two sections and begin to dive into the heart of the matter of this paper, the following analysis discusses the gap in the literature.

While many academic articles evoke the close link between socioeconomic disparities and air pollution, they mainly focus on local urban scales and single-factor analyses. Thus, the gap in the literature stands in the lack of national empirical analysis combining spatial air quality data with socioeconomic indicators, through an intersectional approach, for an entire territory. The literature review has demonstrated a broad consensus among scholars studying environmental inequalities. In fact, exposure levels of air pollution vary significantly across population groups, with pollution consistently concentrated in more socially and economically vulnerable areas. While the body of academic research on environmental inequalities is growing, it is not yet complete since it lacks large-scale analysis combining different socio-economic parameters.

The details of the empirical research and the method used are set out in the following section.

Method and Theoretical Framework

This research adopts an environmental justice framework combined with spatial inequality analysis to examine how socio-economic stratification structures differentiated exposure to air pollution in Belgium. It explores the question “*who breathes what?*” through a data-driven exploration of air quality exposure and aims to investigate whether socio-economic indicators influence air pollution concentration across the country, using the municipal level as the primary spatial unit of analysis, allowing a relevant spatial comparison.

The empirical analysis is based on the air quality data produced by IRCELINE, the Belgian interregional competent authority responsible for monitoring air pollution. The analysis focuses

on three main pollutants, that are presented in Section 2: PM_{2.5}, PM₁₀ and NO₂, selected for their relevance on the social level. They are monitored by the same network of air quality stations, enabling cross-indicator comparisons. Sometimes, specifically for NO₂, values are occasionally missing for certain stations, as not all monitoring stations measure the same set of pollutants (*see Annex II*). All concentration pollutants values used in this analysis are annual averages for the year 2025. In parallel, socio-economic indicators were chosen from their social relevance as well as the data available on Statbel.be, the Belgian Statistical Office collecting and producing data on the Belgian economy, society and territory. Statbel data is collected using administrative data sources and surveys based on high quality scientific methods. For the operationalization of the relationship between air pollution concentration and socio-economic indicators, the following variables have been analyzed: median annual gross income (data from 2023), average real estate prices for houses with two or three street-facing sides (data from 2025) and the administrative risk of poverty (2023).

The **main objective** of the study is to first understand how IRCELINE data is produced, how they are constructed, their spatial resolution (based on the IFDM-RIO 4x4m² resolution model) and their limitations for environmental analysis. The **second objective** is to explore whether differences in air pollution exposure coincide with socio-economic disparities. To do so, it uses simple descriptive statistics and basic spatial analysis, particularly the Pearson's correlation coefficient. Ranging from -1 to +1, this coefficient (often written r) allows us to measure the linear relationship between two or more variables. An r value between 0 and 0.1 is referred to as no correlation. An r value between 0.7 and 1 is referred to as a very strong correlation ([Leon, 1998](#)). The following section dive into the heart of the topic and tries to answer the research question.

Empirical Analysis Section

The first empirical section examines how IRCELINE produces its spatial air quality data and the limitations inherent to that process. It first presents and critically evaluates the methodology, before identifying the boundaries of such data analysis. In the second part, it will turn into a descriptive analysis linking air pollution data in Belgium to socio-economic factors with maps to lean on the analysis.

Part. 1 : Delving into IRCELINE's spatial air quality data

Following the EEA, “data on emissions are necessary for understanding the causes and consequences of air pollution and for designing effective policy responses.” ([Air Quality in Europe, 2022 Report](#)). This first section focuses on the statistical methodology of air pollution, as well as identifying the most significant air pollutants and their characteristics. Then, it will present the limits of IRCELINE methodology and the challenges around collecting air pollution data.

Presentation of IRCELINE monitoring stations

The particularity of Belgium is that it is divided into three main parts: Flanders, Brussels, and Wallonia, each having its own competent authority. In Flanders, it is Flanders Environment Agency's (VMM) competences to measure, evaluate, and create air quality policy plans. The Interregional Environmental Unit (IRCELINE) is the competent authority for national and international reporting obligations on air quality matters in Belgium. It is a network of automatic monitoring stations spread across the country measuring pollutants such as ground-level ozone, nitrogen dioxide, particulate matter (PM₁₀, PM_{2,5}), sulfur dioxide, benzene, and others. Air quality monitoring networks in Belgium are used to assess air quality in accordance with the European directives on air quality (2008/50/EC & 2004/107/EC). The following map shows where the monitoring stations are located all over Belgium:

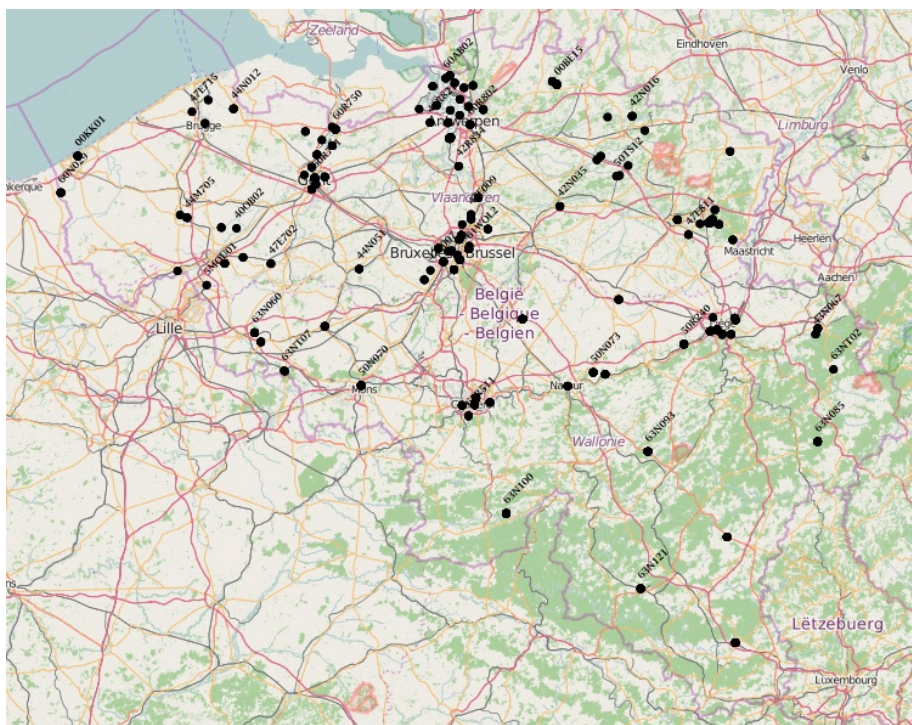


Figure 1 : Air Quality Monitoring Network of Belgium, INSPIRE Geportal (2015)

The 158 monitoring stations don't analyze the same indicators or pollutants: out of 23 parameters, about 16 directly measure air pollution, and 6-7 are meteorological or contextual indicators. The table in *Annex I* summarizes the parameters monitored by IRCELINE and their functions.

Air quality data in Belgium is produced through a two-step process: in situ measurement that is, the direct collection of pollutant concentrations at these fixed monitoring stations, followed by a spatial modelling which extends the measurements to the entire country. On the IRCELINE website, air quality data is real-time measurement on a daily basis.

IRCELINE's methodology

The overall objective of IRCELINE's assessment models is to map pollutant concentrations, particularly based on measurements taken at a number of monitoring stations. The models used assess air quality over a given period, especially by calculating the population's exposure to high concentrations of pollutants ([Irceline](#)).

The two assessment models used in IRCELINE are the RIO interpolation method and the IFDM model. Both models allow to assess air quality in the entire country. On one side, the RIO-interpolation model uses available measurements from the fixed measuring stations and interpolates them in a way using land cover data. On the other side, the IFDM calculates the impact of emissions of point and line sources on the air quality in the direct surroundings of those point and line sources ([Vanpoucke & Roet, 2022](#)). Following these air quality modelling specialists, the main strengths lie in the high spatial resolution (at street level) and a high time resolution (hourly). These models are particularly effective in detecting hot spot locations (high concentrations of pollutants), and also in calculating exceedances of EU air quality thresholds.

Limits of IRCELINE's spatial modelling data

Despite the efficiency of such spatial modelling methods, it is still relevant to question the limits of such data particularly its social blind spot. First of all, there is a lot of bias in air pollution data since there is an uneven coverage of monitoring stations, some errors or uncertainties in emissions inventories, and simplification assumptions in atmospheric simulations. To overcome these biases, IRCELINE implements few mechanisms such as regular calibration and maintenance of monitoring stations, use of multiple data sources, improvement of emissions inventories, among others. Beyond specific technical loopholes, the spatial mapping of air quality in the EU does not include socioeconomic indicators in the creation of maps. The social dimension is completely absent from the data production, the only lever is mixing both

urban and rural maps based on their population density, not on social indicators (Horálek et al., 2006). One similar critique has been made by Janssen et al. (2012) in their article *Spatial interpolation of air pollution measurements using CORINE land cover data*. The authors argue that traditional interpolation methods are insufficient to capture regional patterns and local variations in pollution levels, mainly because these are strongly influenced by land use and human activities. To overcome this limitation, they incorporate CORINE land cover data, a European land-use database, in order to better account for local environmental characteristics that may affect air pollution differently across territories (e.g. urban areas, industrial zones, forests, agricultural land). They conclude by stating that integrating further information significantly improves the spatial representation, and therefore the accuracy of such data.

Following their point of view, the methods used by IRCELINE are insufficient for gaining an intersectional understanding of air pollution inequalities, even though this is one of the key factors to consider when discussing environmental inequality (*see literature review section*). Therefore, in the following section, the study will attempt to use cross-sectoral data in order to better capture the interaction between environmental exposure and socioeconomic vulnerability.

Part. 2 : Linking Air Quality to Socio-Economic Inequalities

This second section will explore the relationship between air pollution in Belgium and socio-economic variables chosen in the Method and Theoretical Framework section. First, it will present the properties and justify the choice of pollutants, and then it will dive into the data collected and present the results as well as discussing them.

Air pollutants as indicators of environmental inequality: PM2.5, PM10, NO₂ and BC

Particulate matter (PM2.5 and PM10) originates mainly from road traffic, residential wood and coal combustion (i.e. heating), industrial activities and construction sites. These particles, measuring less than 2.5 or 10 micrometers in diameter, consist of solid particles and liquid droplets emitted through combustion processes, fires and industrial emissions. Exposure to particulate matter is associated with respiratory and cardiovascular diseases, lung cancer and premature mortality, and to a certain extent ecosystem damage.

Black carbon (BC), a component of PM2.5, is produced through the incomplete combustion of fossil fuels, wood, and waste. Its main sources include road traffic, residential heating, and industrial activities. Black carbon is a relevant indicator of traffic-related and urban environmental inequalities (i.e. diesel traffic, domestic heating).

Nitrogen Oxides (NO_x), particularly nitrogen dioxide (NO₂), refer to a group of highly reactive gases emitted by road transport (diesel and gasoline engines), power plants and industrial combustion, boilers and gas turbines. These pollutants contribute to respiratory irritation, reduced lung function, and the acidification and eutrophication of ecosystems ([Climate & Clean Air Coalition](#)).

PM_x, NO_x and BC are particularly relevant for the analysis of socio-economic inequalities as their concentrations are strongly linked to proximity to major roads, industrial zones, often overrepresented in urbanized areas. Due to historical patterns of industrial development and socio-spatial segregation, road traffic constitutes a key factor influencing pollution level. Industrial infrastructures (e.g. factories, power plants, port areas) emit PM_x and heavy metals, and are historically concentrated in working class areas. Lastly, residential heating can also reflect socio-economic disparities, as households experiencing energy poverty are more likely to rely on cheaper and more polluting heating systems, increasing PM_{2.5} and BC emissions. The social class and urban-rural approach is key to understanding the results in the following sections, as stated by Bullard, racial and social hierarchies contribute to creating or widen environmental inequalities in poor, working-class, and urban communities ([Bullard, 1996](#)).

These four pollutants will be analyzed in relation to three socioeconomic factors, which are discussed in the following methodological section.

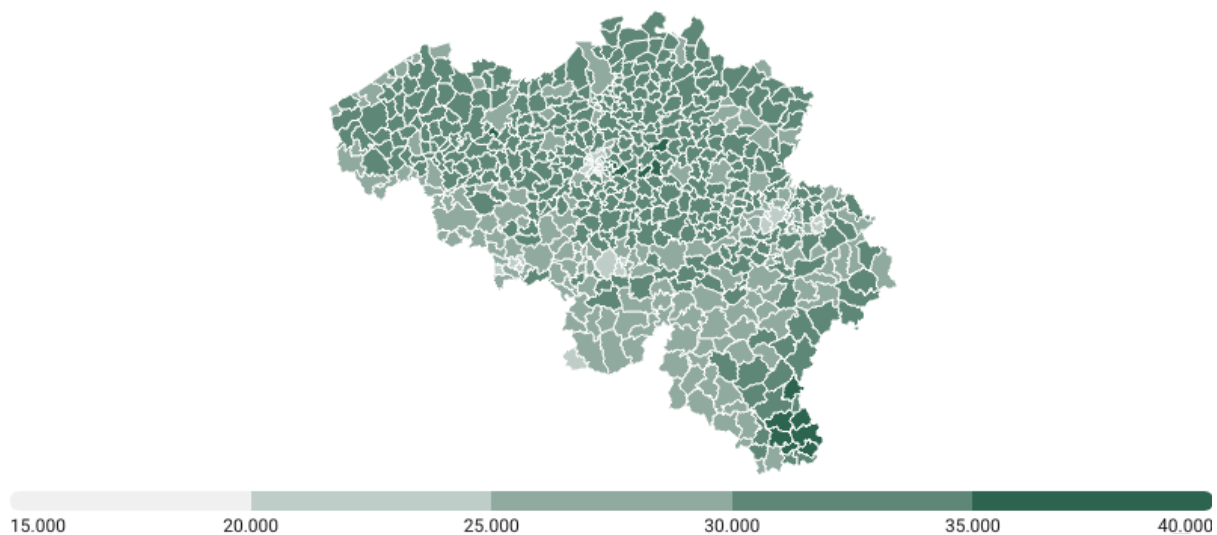
Data overview and methodological considerations

To assess whether the socio-economically disadvantaged populations are more exposed to air pollution, this study relies on IRCELINE spatial monitoring stations for air pollutants across Belgium. The dataset includes 81 monitoring points each for PM_{2.5} and PM₁₀, 29 monitoring points for BC and 69 for NO₂ (see Annex II for all municipalities covered). Each monitoring point is associated with one or more measurement stations depending on the pollutant and the geographic area (e.g. Antwerp includes 17 stations). The monitoring coverage is uneven across pollutants neither spatially heterogeneous, that is why this study could contain some bias at the spatial level, and therefore in the results.

The analysis is combined with three main socio-economic indicators, used as explanatory variables: annual median income, houses prices, and risk of poverty at the municipal level. These variables have been chosen for relevance with socio-economic inequality, directly linked to material deprivation.

The **first socioeconomic indicator**, the median annual income, is based on the most recent official 2023 data published by Statbel in November 2025. The proposed map was useful to identify the municipal income and then match it to each monitoring point in the Table available in *Annex II*. Below is the relevant map for the gross annual median income (in €), varying from €20 862 for Saint-Josse-ten-Noode to €44 066 for Atttert. In Belgium, income levels are traditionally higher in Flanders, the Dutch-speaking region than in Wallonia, the French-speaking region. This is shown on the map, where Wallonia presents light green.

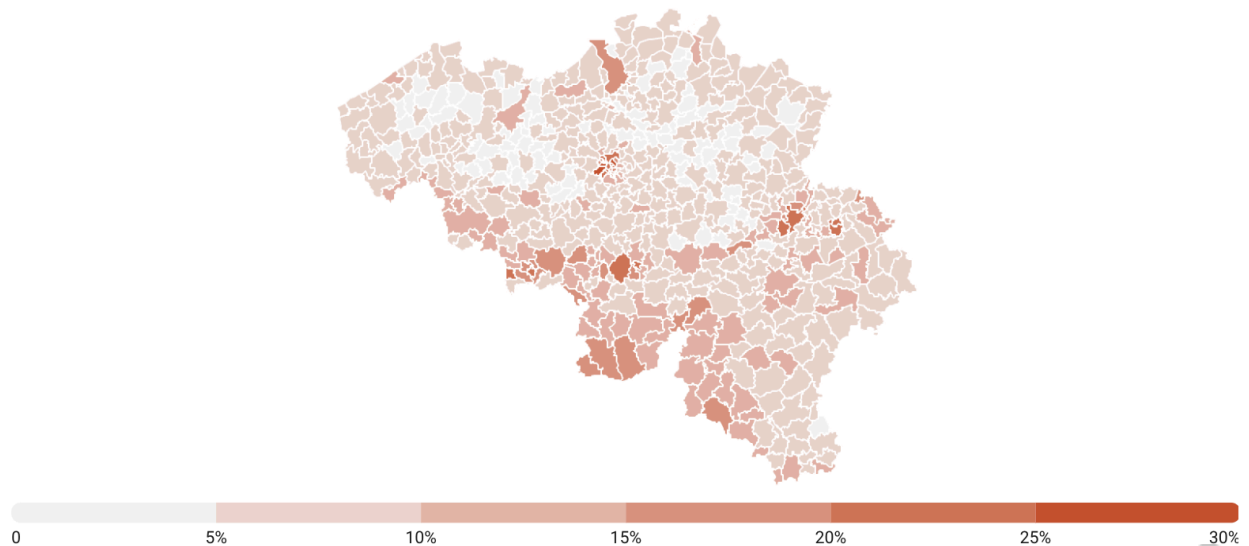
Figure 2 - Median income at the municipal level in Belgium in € (Statbel, 2023)



The **second socioeconomic indicator**, the risk of poverty, refers to the proportion of the municipality's population whose income is below the national poverty line. In Belgium, according to Statbel and in accordance with median income, poverty risk levels are lowest in Flemish municipalities, the highest are in the Brussels-Capital Region. In 2025, 16,5% of the Belgian population is exposed to poverty risk or social exclusion, that is about 1,9 million people (SILC, 2025). To be considered at poverty risk one has to be at risk of income poverty (10,9%), live in a low-work-intensity household (11%), and face severe material and social deprivation (4,9%). It should be noted that social exclusion and poverty rates have declined over time, falling from 20.1% in 2019 to 16.5% in 2025. The risk of poverty varies from 3,4% for the lowest in the municipality of Zemst in Flanders, and 26% for the highest in the municipality of Schaerbeek in

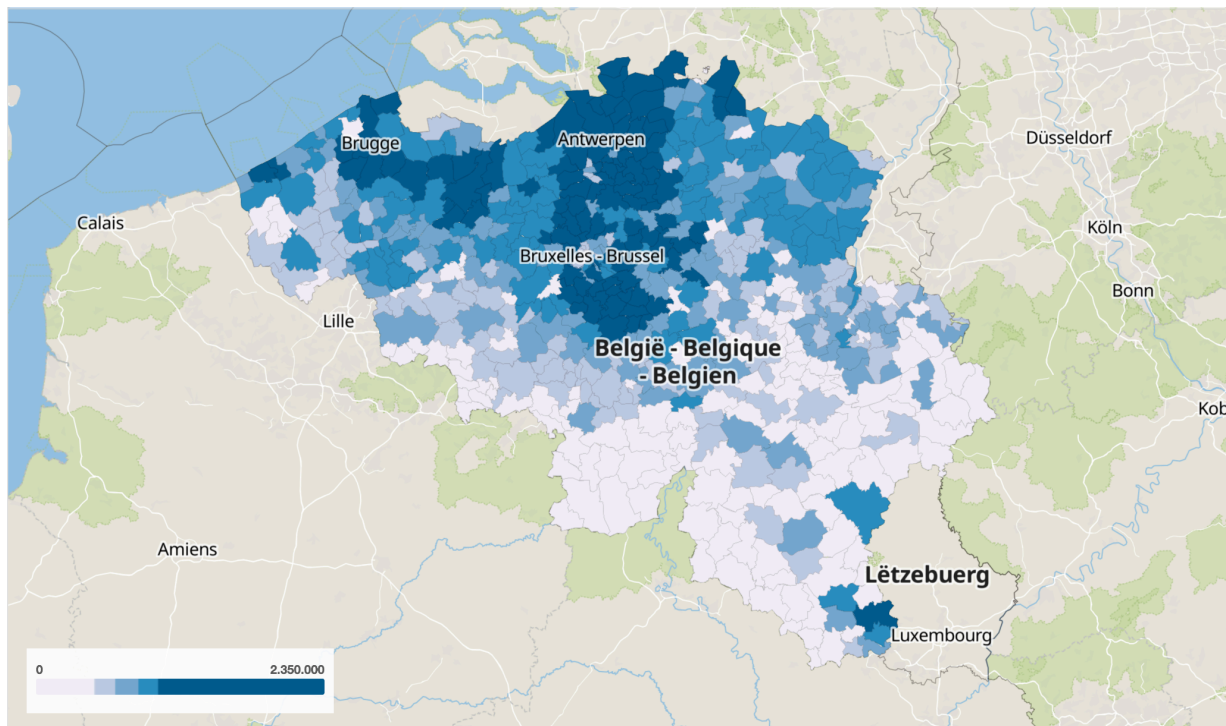
the Brussels-Capital Region. Below the map which enabled this study to determine the percentages of risk poverty for each municipality recorded by the monitoring stations.

Figure 3 - Administrative poverty risk at the municipal level in Belgium in % (Statbel, 2023)



Lastly, the **third socioeconomic indicator**, the real estate prices for houses with two or three street-facing sides, is a more indirect socio-economic variable. However, it allows the study to connect, or not, the first two other indicators and measure if pollution is linked to real estate prices. Statbel publishes the figures annually by building type (apartments, single-family homes, median price by building type). In 2025, the Brussels-Capital Region was the most expensive region with prices ranging around 510 000€ for detached and semi-detached homes. The Walloon Region was the least expensive region, with a median price of 198 000€ for detached and semi-detached homes. The choice of houses with two or three street-facing is justified as they represent the most standardized and widespread type of property in Belgium, which allows for better comparison and analysis. This indicator is interesting as it is grounded in the hedonic pricing theory, which refers to a method used to evaluate the economic costs and benefits associated with environmental quality, including air quality and proximity to industrial or traffic-related pollution sources (Paudel, 2020). The following map presents the house prices by municipality, figures that were recorded in the same way as for the other two indicators so that averages and correlation coefficients could be calculated.

Figure 4 - Average real estate prices for houses with two or three street-facing sides in € (Statbel, 2025)



Together, these three socio-economic indicators provide a multidimensional picture of socioeconomic disparities among different regions at the municipal level in Belgium. Combined with the IRCELINE stations surveyed, this forms the analytical framework upon which the following section builds the core analysis and the answer to the research question.

Correlation analysis and results

As exposed in the Methodological and Theoretical section, this part will use the Pearson coefficient, allowing to produce simple results. From $r=0.5$ to $r=1$ or $r=-0.5$ to $r=-1$, the relationship between two variables is strong, the points lie very close to a straight line. From $r=0.2$ to $r=0.5$ or $r=-0.2$ to $r=-0.5$, the relationship is weak, the data points are scattered, but an overall trend is visible. A result close to $r=0$ indicates a relationship is null whereas a result close to $r=1$ or $r=-1$ is a perfect correlation. The following *Table 1* presents the results for all socio-economic indicators and all four pollutants, produced in the Excel sheet thanks to using the function =PEARSON(.

Table 1 - Pearson correlation coefficients between pollutant concentrations and socio-economic indicators in Belgium (Mayot, 2023-2025)

Socio-economic indicator	PM2.5	PM10	BC	NO2
Gross median annual income (2023)	0,157	0,027	-0,085	-0,254*
Average estate prices for houses (2025)	0,512*	0,463*	0,503*	0,426*
Administrative poverty risk (2023)	-0,225*	-0,077	0,191	0,244*

• Positive, significant ($p < 0.05$) • Negative, significant ($p < 0.05$)

$p < 0.05$

Overall, there is no strong or outstanding correlation between these variables, however some results are interesting when comparing low income and socio-economic disparities with air pollution. Among the four pollutants analyzed, **NO₂** provides the most consistent evidence in support of the hypothesis that socio-economically disadvantaged populations bear the highest cost of air pollution and environmental inequalities. NO₂ concentrations show statistically significant associations with both administrative poverty risk ($r = +0.244$, $p < 0.05$) and with gross median annual income ($r = -0.254$, $p < 0.05$). Municipalities with higher risk of poverty and with less median income are the most exposed to NO₂. Since NO₂ is primarily emitted by road traffic, and disadvantaged neighborhoods are often crossed by major highway roads, the results are encouraging and are also consistent with the literature.

The picture is more complex for particulate matter. For PM2.5, the relationship with poverty risk is weak ($r = -0.225$, $p < 0.05$) however statistically significant and points in the expected direction. However, a more surprising and unanticipated finding is the strong positive correlation between PM2.5 concentrations and average estate prices for houses ($r = +0.512$, $p < 0.05$). Municipalities with higher house prices tend to also record higher PM2.5 levels. This seems to contradict the hypothesis, but it can be explained by the role of industrial emission as this pollutant does not come mainly from traffic but also industry (i.e. Antwerp, Ghent) which are located in economically active areas with high real estate prices. One might have expected the highest real estate prices to be concentrated in the wealthiest and least polluted municipalities, such as Uccle in Brussels, which combines a high median annual income (€30,163), abundant green space, and comparatively low pollution levels. This shows that the relationship between wealth and pollution is not straightforward and depends heavily on the type of area. A similar pattern appears for PM10, with a relatively significant correlation for house prices ($r = +0.463$, $p < 0.05$), suggesting

that particulate matter is more driven by land use and industrial activities rather than socio-economic factors, at least at the national scale. Also, PM10 originates in different sources and the sample analyzed in this study does not allow for definitive and precise conclusions to be drawn about this pollutant. Similarly for black carbon, the sample is too small with only 29 stations and municipalities covered and analyzed. The results for this pollutant are not significant and therefore do not shed light on its connection to social factors and those related to environmental inequalities.

Although there is a very strong correlation between poverty risk and median annual income since they are complementary, the indirect variable of real estate prices does not appear to confirm our hypothesis or serve as a good measure for analyzing socioeconomic factors. In Belgium, real estate prices primarily reflect urbanization (i.e. prices in Brussels and Antwerp), which are locations that have the highest levels of pollution.

Limits of the results

Although this study partially demonstrates the link between socioeconomic factors and air pollution, on this scale, it has a number of limitations, which are discussed in this section. First, as mentioned in the previous sections, the IRCELINE monitoring stations do not cover the entire territory, which creates a selection bias that is difficult to account for. The spatial bias is central to this research and does not provide a comprehensive view of the entire territory of Belgium, which makes other national studies difficult, even though they are essential and useful to environmental inequalities literature. On the other hand, the samples collected in the selected municipalities for NO₂ and black carbon have concentrations that are too low, resulting in higher p-values and making it more difficult to statistically confirm the correlations.

Air pollution and environmental inequalities are complex phenomena, and they depend on a multiple of factors. The analysis of IRCELINE stations, which combine urban and rural areas, is also one of the limitations, as has already been noted in the literature. Since correlations may be much stronger at the intra-urban level, the decision to conduct a national analysis is therefore a limitation in itself. As stated by Carvalho et al. (2022), there is a need for a scale-dependent research.

Conclusion

Confronting the results, it seems that socio-economic indicators in relation to air pollution in Belgium offer a partial and nuanced answer to the research question. In fact, there is a consensus in the literature that the most economically disadvantaged and marginalized groups are bearing the brunt of climate change, as well as the highest concentrations of air pollution globally. However, at the national scale of Belgium, the analysis reveals that socio-economic inequalities in air pollution exposure are pollutant-specific. NO₂ shows the most consistent pattern of environmental inequality: the data suggest that poorer municipalities are more exposed to NO₂ (higher poverty risk rates and lower median incomes), which indicates that the burden of traffic-related pollution falls disproportionately on disadvantaged populations. Therefore, it answers the spatial segregation question as lower-income households have less residential choice, and are more likely to live near major road axes as house prices are lower and often far from city centers. For particulate matters, PM_{2.5}, PM₁₀ as well as for Black Carbon, the limitations of the study (i.e. spatial biases, small samples, scale) do not allow us to draw precise conclusions or identify strong correlations. The descriptive correlation method using Pearson's correlation coefficient is just one of many methods for identifying links and rational explanations behind these scientific variables. There are, of course, other factors that explain environmental inequalities, and this study is just one example of them.

In conclusion, this research paper aimed to resolve one gap in the existing literature by conducting a national empirical study of air pollution concentration in Belgium in relation to socio-economic indicators. However, as highlighted in the literature, modern research on environmental inequalities and differentiated exposure needs to adopt an intersectional perspective and methodology. Further studies examining how air pollution affects people living in Belgium differently depending on their social status, gender, class, ethnicity, or migration background, would provide a more complete picture of such complex social and essential climate issues.

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Annex I

Table 2 : List of the 23 parameters monitored by IRCELINE (n.d)

Category	Parameter	Role
POLLUTION	Nitrogen Dioxide (NO ₂)	EU-regulated pollutant
	Nitrogen Monoxide (NO)	EU-regulated pollutant
	Ozone (O ₃)	EU-regulated pollutant
	Sulphur Dioxide (SO ₂)	EU-regulated pollutant
	Carbon Monoxide (CO)	EU-regulated pollutant
	Particulate Matter < 10 µm (PM10)	EU-regulated pollutant
	Particulate Matter < 2.5 µm (PM2.5)	EU-regulated pollutant
	Particulate Matter < 1 µm (PM1)	Unregulated pollutant
	Particle number concentrations (10-800nm)	Unregulated pollutant
	Black Carbon (BC)	Combustion indicator
	Benzene	EU-regulated pollutant
	Toluene	Volatile organic compound
	Ethylbenzene	Volatile organic compound
	1,2-Xylene / O-Xylene	Volatile organic compound
	M+ P Xylene	Volatile organic compound
	Ammonia (NH ₃)	Precursor to fine particulate matter
GHG	Carbon Dioxide (CO ₂)	GHGs, excluding strict air quality standards
	Elemental gaseous mercury	Global pollutant / toxic
METEOROLOGY	Atmospheric Pressure	Weather conditions
	Relative Humidity	Weather conditions
	Temperature	Weather conditions
	Wind Direction	Dispersion of pollutants
	Wind Speed	Dispersion of pollutants

Annex II