CURIEUZENAIR

The largest citizen science project on air quality ever carried out in Brussels

Data collection, data analysis and results

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CONTENT

This report provides a description of the scientific research during the citizen project CurieuzenAir, which has mapped the air quality (atmospheric NO_2 concentrations) across the Brussels Capital Region in October 2021. The report describes (1) the data collection with the help of citizens, (2) the quality control and processing of data, and (3) an overview of the resulting dataset.

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Synopsis

1.1 Objectives

The prime objective of the citizen science project CurieuzenAir was to map the air quality across the Brussels Capital Region with unprecedented spatial detail, and in this way, to provide a reliable estimate for the exposure to NO_2 for all inhabitants of the Brussels Capital Region. NO_2 forms an important indicator of traffic-related air pollution and has substantial health impacts at higher ambient concentrations. In addition to the scientific objectives, CurieuzenAir aims to raise awareness about air quality and the importance of a healthy living environment. The CurieuzenAir project is an initiative of University of Antwerp, Brussels' city movement BRAL and Université Libre de Bruxelles with the support of Bloomberg Philanthropies, Bruxelles Environnement and the Brussels Capital Region, and in close cooperation with mardia partners Le Soir, De Standaard, BRUZZ, and logistic partner DPD.

1.2 Approach

The CurieuzenAir project (2021; 3.000 measurement locations) uses a similar approach and methodology as the CurieuzeNeuzen citizen science projects on air quality conducted in Antwerp in 2015 (2.000 measurement locations) and Flanders in 2018 (20.000 measurement locations). Candidate participants were recruited via a broad media campaign. In parallel, the city movement BRAL organised a community trajectory, reaching out to people who are less accessible through traditional media channels. This way, CurieuzenAir aimed to be an inclusive citizen science project that engages all members of society, independent of sociocultural status, gender, age or education level.

Three thousand sampling kits were distributed to participants that either lived (households), studied (schools) or worked (companies and institutions) within the Brussels Capital Region. The sampling kit allowed for the detection of the ambient NO_2 concentration. As the Brussels Capital Region has a total surface area of 161 km^2, the deployment of 3.000 sampling kits implies an average spatial sampling density of 19 measurement locations per km^2. A robust and easy-to-install setup consisted of a real-estate measurement panel and two Palmes diffusion tubes. The latter were used to measure the NO_2 concentration over a four-week period (from 25 September 2021 to 23 October 2021). Using data collected in parallel at reference stations of Environnement Bruxelles, the mean annual NO_2 concentration for 2021 was estimated at all measurement locations.

NO_2 concentrations (indicative annual means) are shown on an interactive map. Exceedance levels above the European Air Quality Directive (40 µg m^{-3}) and the World Health Organisation (10 µg m^{-3}) guidelines are calculated, and put into historical perspective.

Main conclusions

1. CurieuzenAir provides a unique high-resolution scan of the air quality across a major European city (Brussels). Air quality data was collected at 3.000 measurement locations with the help of citizens. A high percentage of measurements (83%) passed all quality control criteria. As a result of the high sampling density, the CurieuzenAir dataset enables a reliable estimate of the exposure to NO_2 for all inhabitants of the Brussels Capital Region. This type of data collection is unique at the international level.

2. CurieuzenAir reveals the impact of traffic emissions on air quality across Brussels with unprecedented detail. Air quality varies substantially across the Brussels Capital Region: NO_2 concentrations show a ten-fold increase between the lowest value (6,2 µg m^{-3}) and the highest value (60,5 µg m^{-3}). CurieuzenAir reveals both local hotspots of NO_2 pollution (1,4% of the locations are above the EU threshold of 40 µg m^{-3}) as well as urban zones with very good air quality (1,6% of the locations remain below the WHO threshold of 10 µg m^{-3}). Local traffic emissions and poor ventilation in street canyons appear the main drivers of the observed differences in air quality.

3. CurieuzenAir confirms that air quality in Brussels has substantially improved in recent years. The exceedance level (i.e., the percentage of locations above the EU limit of 40 µg m^{-3}) is only 1,4 % in 2021, which is low when put in a historical perspective. The CurieuzenAir dataset hence underscores the improvement in air quality over the last decade (the estimated exceedance level was at 50% in 2010 and 10% in 2019). This improvement is attributed to a reduction in NO_2 emissions resulting from both better technology (stricter emission targets imposed by EU legislation; increased use of SCR “AdBlue” technology; adoption low-emission zone) as well lower traffic intensities (telework stimulated by COVID19 pandemic; low-traffic pedestrian areas; increased cycling).

4. Street-level air pollution by NO_2 continues to have a substantial health impact on the population of Brussels Capital Region and will continue to do so in the future. Recently, the World Health Organisation has revised its guidelines and has put forward the threshold level of 10 µg m^{-3} as the concentration level (annual mean) at which health impacts first start to emerge. The CurieuzenAir dataset reveals that 98,6% of the population in Brussels lives or works at a location that exceeds this threshold value.

5. CurieuzenAir reveals a clear pattern of “air inequality” across the Brussel Capital Region. There is a clear link between the socio-economic status of the inhabitants in Brussels and the air quality (annual NO_2 concentration) at their home location. Areas with a higher population density experience higher NO_2 levels, and people with a higher income tend to better air quality at their home location (despite having more cars).

6. CurieuzenAir illustrates the power of large-scale citizen science. The extensive data collection in CurieuzenAir was not possible without the enthusiastic assistance of 1000’s of citizens. The CurieuzenAir dataset has provided unprecedented insights into the patterns and drivers of air pollution, which can help to improve models and better inform future policies. This way the citizens of Brussels have made a direct contribution to a better environmental policy across the Brussels Capital Region.

7. CurieuzenAir not only provides detailed data for Brussels, but also shows patterns and trends that are highly relevant for other European cities. While the COVID-induced reduction in traffic intensity is likely temporary, part of the observed improvement is linked to EU air quality policy and will be permanent. We contend that these effects are not specific to the context of Brussels. If CurieuzenAir-type data collection would be applied in other EU cities, they will likely show similar patterns and trends. In this sense, the CurieuzenAir forms a relevant case study for the impact of air quality policies across all European cities.

Chapter 1: CurieuzenAir dataset

1.1 Measurement locations

1.1.1 Registration of candidate participants

The CurieuzenAir project started on 21 May 2021 with the launch of the CurieuzenAir website (www.CurieuzenAir.brussels). At the same time, a multimedia campaign was launched to recruit sufficient candidate participants (3.000 measurements kits were made available by the project). Advertisements (print and video) were published in newspapers (Le Soir and De Standaard), aired on Brussels' radio and television (BRUZZ), displayed on posters in the metro (Out-of-Home advertisement), and distributed via social media channels (Facebook, Twitter). Candidate participants could register to join the project and propose a measurement location via an online form. This form was accessible through the CurieuzenAir website as well as the websites of the three media partners (Le Soir, De Standaard, BRUZZ).

During the registration process, the candidate participants provided personal contact information following GDPR regulations (name, e-mail and address) as well as metadata about the suggested measurement location. The metadata included (1) the type of registration (school, organisation/company, or private household), (2) information on where exactly the measurement panel would be placed: the location (address), height (floor) and orientation (window facing street, side or back of the house) and (3) a personal assessment of the traffic intensity and the density of trees within the street of the measurement location. This metadata was used in the subsequent selection process of the measurement locations (see below).

The recruitment period lasted for three weeks. During this period, the number of registrations was continuously monitored (Figure 1) and a local "enthusiasm index" was determined (i.e., number of candidates already subscribed in relation to the total number of inhabitants in a municipality of Brussels, Figure 2). To obtain suitable coverage over the entire Brussels Capital Region, targeted social media advertisements were set up for zones and municipalities where the enthusiasm index was lower than average, and hence registrations were lagging.

After three weeks, on 13 June 2021, the recruitment campaign ended, and the registration process was closed. In total 5.908 candidate locations registered to participate in CurieuzenAir. Most of these candidate subscriptions were private households (n = 5.445; 92,2%), followed by companies and organisations (n = 356; 6,0%) and schools (n = 107; 1,8%) (Table 1).

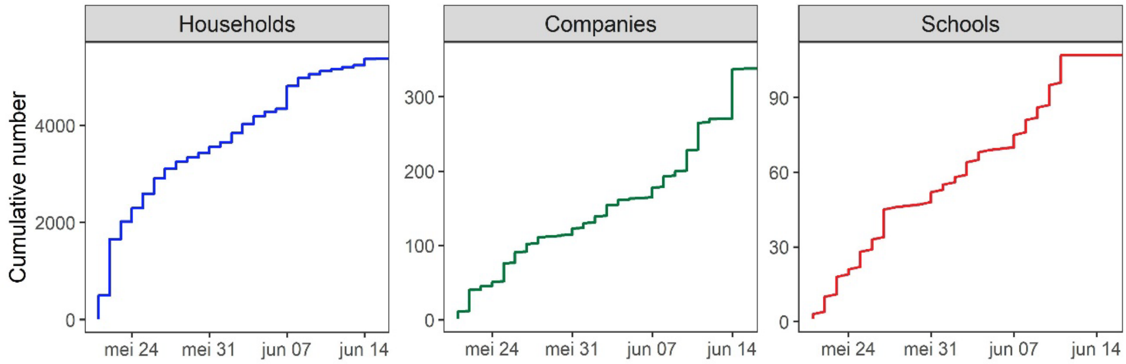


Figure 1. The cumulative evolution of candidate subscriptions to the CurieuzenAir project. The registration period lasted three weeks (21 May to 13 June 2022). Registrations are subdivided over the three registration types: (1) private households, (2) companies and organisations, and (3) schools.

The Brussels Capital Region has 1.219.970 inhabitants in total (data for 2021; bisa[1]), which implies that on average 4,8 people per 1000 inhabitants registered as a candidate participant for CurieuzenAir. However, more people become directly involved and aware of the project per individual registration. If we assume that a private household accounts for 2,1 people (the average size of a Brussels household[2]), an organisation/company include 15 people, and a school reaches 200 persons, we estimate that ~3% of the Brussels population became directly connected to the CurieuzenAir project in the start-up phase.

Table 1. Overview of candidate and selected measuring locations in CurieuzenAir. Subscriptions are subdivided over the three registration types (i.e. private households, companies and organisations and schools) and the relative number of candidates per type is indicated. From the total pool of candidate locations, a selection was made using a custom-developed computer algorithm to obtain a representative selection and optimal spatial coverage over the entire Brussels Capital Region.

	Candidates		**Selection**	
Registration type	**Absolute**	**Relative (%)**	**Absolute**	**Relative (%)**
Private households	5.445	92,2	2.635	87,83
Companies and organisations	356	6,0	282	9,40
Schools	107	1,8	83	2,77
Total	**5.908**	**100**	**3.000**	**100**

[1] bisa.brussels/themas/bevolking/jaarlijkse-evolutie
[2] https://environment.brussels/state-environment/report-2011-2014/brussels-context/demographic-evolution-brussels-region

The recruitment campaign succeeded to reach out to different communities in the Brussels Capital Region. Participants registered for 47,7% as native Dutch speaking, 47,0% as French speaking, while the remaining 5,3% opted to be contacted in English. At the end of the campaign, participant subscriptions showed a satisfying geographic spread and coverage across the Brussels Capital Region. The final "enthusiasm index" ranged between 2,9 in Evere and 6,0 in Forest (expressed as candidate participants per thousand inhabitants; Figure 2). Hence all 19 municipalities of the Brussels Capital Region were suitably represented (allowing a suitable spatial selection of measurement locations).

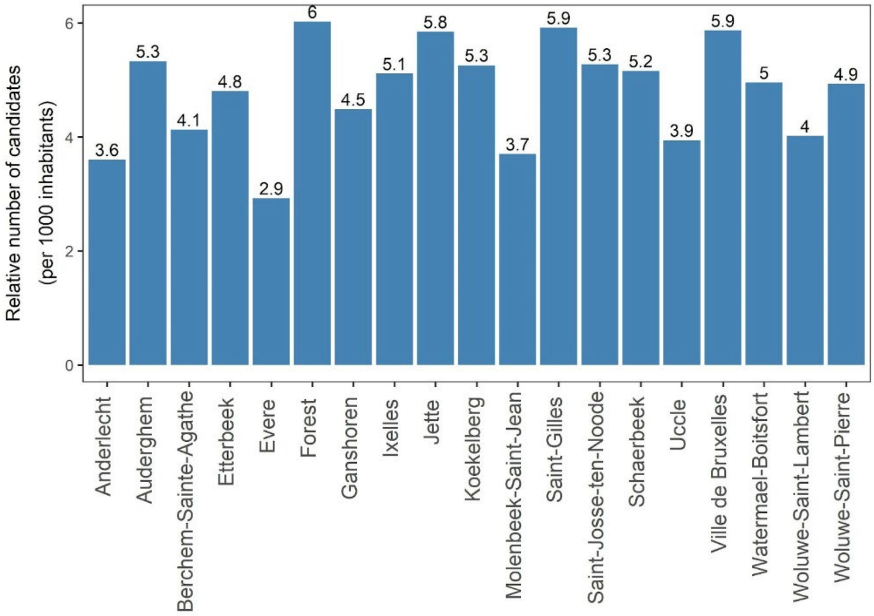


Figure 2. Enthusiasm index for the 19 municipalities in the Brussels Capital Region. The index is calculated as the number of candidate participants per thousand inhabitants subscribed at the closing date of the three-week registration period.

1.1.2 Community and background locations

1.1.2.1 Community trajectory

Overall citizen science projects tend to attract participants that are skewed towards persons with a higher education, male gender and a technological/scientific background (Curtis, 2018; Paleco et al., 2021). Therefore, one of important challenges for CurieuzenAir was to reduce this potential bias and include participants from groups that represent the entire Brussels' population. The goal was to have an inclusive citizen science project and strive for engagement from all members of society, independent of sociocultural status, gender, age or education level. For this reason, CurieuzenAir specifically opted to include so-called **community locations**, i.e., measurement locations that specifically connect to people that have a lower propensity to participate in citizen science projects (and were also expected to be less susceptible/accessible through the media channels used in the recruitment campaign).

To this end, BRAL reached out to local organisations that focus on health and poverty issues, and in this way, socio-economic vulnerable groups were personally approached and asked to participate within CurieuzenAir. Eleven workshops[3] were organised during which BRAL employees were shown around by residents in their local neighbourhood. These workshops had two important goals. The first objective was to make air pollution a topic of discussion. Socio-economic vulnerable groups are often disproportionally affected by air pollution and associated health problems, bur at the same time, they are also less likely to be aware of the problem (Noël et al., 2020). By discussing the causes, health effects and solutions to air pollution in their own neighbourhood, the topic becomes more understandable and tangible. During these workshops, participants could suggest suitable measurement locations in their neighbourhood (e.g. pharmacies or local shops) and had the opportunity to pre-register as a CurieuzenAir community location.

In total n = 202 measurement locations were signed up by BRAL via the community trajectory. At these community locations, the measurement procedure was identical as at the regular CurieuzenAir locations (samplers attached to real-estate panel; Figure 3a) and participants were requested to provide the same information (e.g. metadata and surveys). Yet, to ensure successful participation, these community locations were given dedicated support in multiple ways. Foremost, community locations were given priority during the location selection process (in addition to schools, see below). Secondly, special care was taken to ensure that community measurements were brought to a good end, by providing additional support throughout the project. All community participants were personally assisted during the registration and measurement period. When needed, people were contacted by phone to complete their registration form, the measuring panel was delivered at their home, or people were assisted with the installation of the measurement panel to their window.

1.1.2.2 Background locations

At a specific street location, the detected NO_2 concentration results from contributions of various emission sources: (1) a natural background concentration, (2) an anthropogenic background contribution that results from ‘imported’ polluted air into the street (originating from surrounding streets, neighbourhoods or even from outside the Capital Region), and (3) local traffic emissions within the street itself.

Under natural conditions, NO_2 can be formed under specific circumstances (e.g. forest fires or lightning; emission from microbial activity in soils). In Belgium lowest NO_2 concentrations are measured in the Ardennes, with a minimal NO_2 concentration of 4 $\mu g\ m^{-3}$ detected in the reference stations of Dourbes (Viroinval) and Renuamont (Sainte-Ode; ATMO-Street, irCELine[4], 2020). The actual background concentration within an urban context is typically higher than the natural background concentration.

In order to separate the background effect from within-street NO_2 emissions, we determined NO_2 concentrations at so-called “background locations”, i.e., measurement locations that have no local, nearby urban NO_2 sources. Suitable background locations are typically located in a forested area, large park or car-free pedestrian area, at a distance from local traffic emission sources. In consultation with Environnement Bruxelles, n = 23 locations were selected as on background locations across in the Brussels Capital Region. Among these, n = 18 locations were selected in La Forêt de Soignes, a few metres away from car-free hiking trails. Additionally, background locations were selected in Parc de Bruxelles, in the centre of Le

[3] https://bral.brussels/nl/artikel/volksbuurten-curieus-over-luchtkwaliteit
[4] https://www.irceline.be/en/air-quality/measurements/nitrogen-dioxide/history/no2_anmean_rioifdm

Domaine Royal de Laeken and at the campuses of the International School of Brussels (Watermael-Boitsfort), VUB (Ixelles) and ULB (Ixelles).

Measurements at background locations were executed by researchers from University of Antwerp (and hence not by citizens). The measurement procedure at the background locations was slightly different from the regular CurieuzenAir locations, as measurements panels cannot be suitably attached to trees in parks and forests. Therefore, the passive diffusion tubes were installed in a dedicated cylindrical housing, which is classically used for reference measurements (Buro Blauw; Figure 3b).

Figure 3. In additional to regular measurement locations, dedicated measurements were conducted at community and background locations. (a) Picture of the measurement setup at a community location. (b) Picture of the measurement setup at a background location.

1.1.3 Selection of CurieuzenAir locations

CurieuzenAir had 3.000 sampling kits available upfront, while 5.908 candidate locations were registered in total by citizens. Scientifically, this surplus of candidate participants was highly beneficial, as it allows targeted site selection for the purpose of representative data collection, i.e., ensuring that the distribution of measured NO_2 values at the CurieuzenAir sample locations are representative for the whole population in the Brussels Capital Region (see section below). Hence, the site selection should ensure both suitable geographical distribution (a higher coverage in urban areas with higher population density) as well as a representative selection between different emission environments (a suitable proportion traffic-dense and street canyon locations versus low-traffic and open locations).

The Brussels Capital Region has a total surface area of 161 km^2. Deployment of 3.000 sampling kits thus implies a sampling density of 19 sampling points per km^2, which implies that sampling locations are on average 232 m apart ("as the crow flies" distance). For reference, this can be compared to the CurieuzeNeuzen Flanders project in 2018 (20.000 locations; sampling density 1,5 location per km^2) and the CurieuzeNeuzen Antwerp project in 2015 (2000 locations; sampling density ~10 locations per km^2).

To retrieve the optimal set of 3.000 actual sampling locations from the set of 5.908 candidate locations, a stepwise selection algorithm was implemented. The selection process served to satisfy two separate objectives:

(1) scientific goal: ensuring that the distribution of measured NO_2 values at the sample locations was representative for the whole population, and the impact of street-level emissions becomes apparent

(2) societal goal: maximising the project's societal impact

In a first stage, three types of sites were given priority, and selected by default. To meet the scientific objective, background locations (n = 23) were selected by default. To meet the societal objective, all schools (n = 107) were selected (as classroom participation stimulates STEM education) as well as all community locations (n = 202) contacted by BRAL were selected (as measurements are carried out by a group of persons, thus maximising societal impact).

In a second stage, the remaining n = 2.668 locations were selected from candidate locations registered through the website. To this end, a stepwise procedure was implemented that ensured a good geographical spread of sampling locations (thus sampling across areas with different background concentrations), as well as a suitable coverage of all different "pollution environments" (thus sampling across locations with different emission and dispersion characteristics). In a first step, locations were prioritised that strictly fulfilled the criteria of the standardised measurement setup (positioning on the first floor and facing the street) and at the same time fulfilled the distance criterion (at least 100 m away from a previously selected location). Maximal geographical spread was determined based on the nearest neighbour distance between locations (measured "as the crow flies"). In subsequent steps, the height criteria were relaxed (extended to second, third, fourth and fifth floor locations) until all 3.000 points were selected. At all selected sites, measurements could be conducted on a street facing window. Candidate locations that were not selected, were placed on a reserve list.

When selected, candidates had to confirm their participation by payment of a participation fee. Participants were requested to pay 10% (€ 15) of the total cost of the measurement setup (€ 150). To enable broad participation, a pay-as-you-wish principle was implemented: the suggested participation fee was € 15 with a minimum of € 5. Community locations were excluded from the participation fee. Participants had one week to confirm participation. After one week, an additional selection procedure was carried out to fill in the open spots with candidates on the reserve list. The final map of the selected CurieuzenAir measurement locations (Figure 4a) was published on 13 July 2021.

1.1.4 Representativeness of CurieuzenAir locations

As noted above (*1.1.3 Selection of CurieuzenAir locations*), representativeness of the CurieuzenAir locations implies that the statistical distribution of measured NO_2 values at the CurieuzenAir sample locations (the so-called histogram) corresponds with the whole population in the Brussels Capital Region. The question of representativeness can be posed by following thought experiment: if one would conduct the same NO_2 passive sampler measurements at all the street level addresses in Brussels, would one obtain the same frequency distribution for the NO_2 concentration? To answer this question, one faces two problems. Firstly, the frequency distribution of NO_2 data from the CurieuzenAir project is only available after data collection, and so it cannot be used during process of location selection. Secondly, it is physically impossible to measure the NO_2 at all street level addresses in Brussels. As a result, the frequency distribution of NO_2 concentrations at all street level addresses is unknown, and hence, it cannot be compared to the frequency distribution of NO_2 data as obtained in the CurieuzenAir project.

Still, there is a work around to the problem, as we can assess the representativeness of the selected CurieuzenAir locations prior to data collection through atmospheric dispersion modelling (this procedure is given in detail in Meysman et al., 2020). For this, the modelled NO_2 concentration at each of the 3.000 selected CurieuzenAir locations was extracted from the available NO_2 map provided by the ATMO-Street model (annual mean NO_2 values for 2019; irCELine et al., 2021).

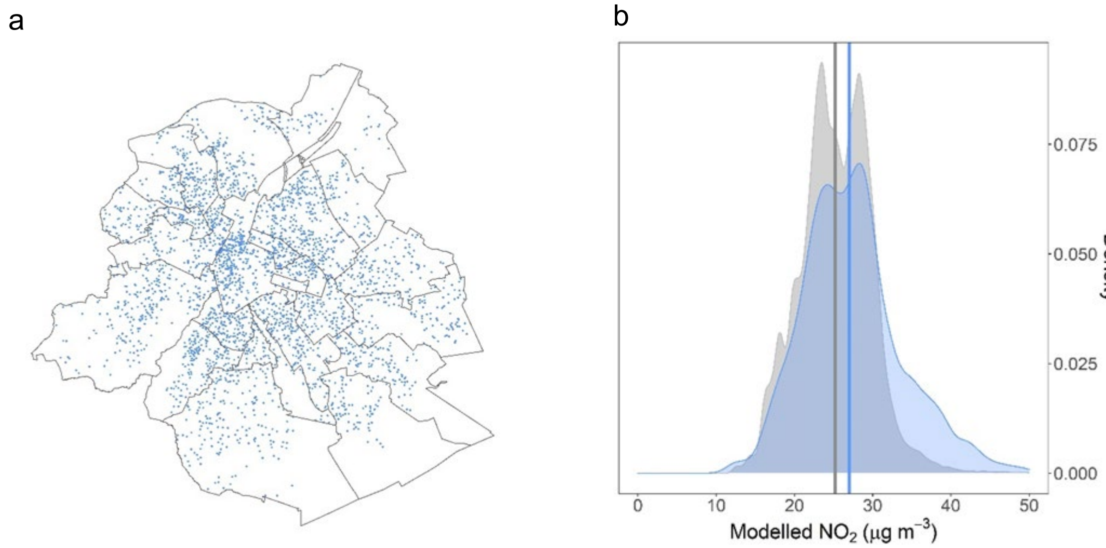


Figure 4. (a) Map of the Brussels Capital Region with the locations of the 3.000 selected CurieuzenAir measurement locations. (b) Frequency distribution of modelled NO_2 concentrations (annual average 2019) at all CurieuzenAir locations (blue histogram, n = 3.000) and all street-level addresses in the Brussels Capital Region (grey histogram; n = 224.996). Vertical lines indicate the median NO_2 concentration for the CurieuzenAir locations (blue line) and all street-level addresses in the Brussels Capital Region (grey line). Modelled NO_2 concentrations were simulated by from the ATMO-Street model (irCELine).

The same procedure was then applied to all the street-level address points in the Brussels Capital Region (n = 224.996; UrbIS database, UrbAdm - Address Points: Entity Address Point[5]). The histograms of these two datasets are given in Figure 4b and show an overall good agreement. Both histograms show a similar range and bimodal frequency distribution. However, the CurieuzenAir locations show a thicker tail towards the higher concentrations, hence indicating an overrepresentation of high-concentration environments in the CurieuzenAir locations. This is also apparent from the mean NO_2 concentration across the two datasets, which is 25,3 µg m^{-3} for all street level addresses in Brussels compared to the 27,9 µg m^{-3} for the CurieuzenAir locations.

This effect could possibly be explained by the fact that people living near high-concentration environments are more aware/concerned about the issue of air quality, and hence they are perhaps more likely to register as candidate participants. At the same time, it should also be noted that the NO_2 values provided by the ATMO street model are street-level concentrations, while the CurieuzenAir locations are the actual locations where people are living (between first

[5] https://datastore.brussels/web/data/dataset/3febf25d-a21c-4e14-adee-e1b022185314

to fifth floor; “measurement panel attached to the bedroom window”). As the NO_2 values typically decrease with height (Imhof et al., 2005), the actual distribution of the CurieuzenAir measurements will tend to lower values compared to the street-level concentrations. This effect may potentially compensate for the slight bias towards high-concentration environments as seen in Figure 4b. Overall, we consider the distribution of measured NO_2 values at the CurieuzenAir sample locations as representative for the whole population in the Brussels Capital Region, providing a conservative upper-bound estimate for the exceedance at EU threshold value of 40 µg m^{-3}.

1.2 Atmospheric NO_2 measurement

1.2.1 Experimental setup

CurieuzenAir citizen scientists measured atmospheric NO_2 concentrations in front of their house or apartment using a low-cost passive sampler design, previously employed in CurieuzeNeuzen Antwerp[6] and CurieuzeNeuzen Flanders[7]. Several types of passive samplers are available for detection of atmospheric NO_2, which all follow the same measurement principle. The specific passive samplers used in CurieuzenAir were acrylic Palmes Diffusion Tubes (PDT) that contain a stainless-steel mesh coated with 50% v/v triethanolamine/acetone, a selective adsorbent for NO_2 (Buro Blauw, The Netherlands). Passive samplers provide a robust and cost-effective method to measure ambient NO_2 concentrations. An additional advantage is that the measurement principle of passive samplers is easy to explain in layman’s terms, thus facilitating low-threshold participation by citizens.

To standardise measurement conditions across participant locations, participants were requested to position the passive samplers in the “nose” of a real-estate panel that is attached to a window facing the street. These panels are preferentially positioned on the first floor (or higher) to avoid data loss due to theft or vandalism. This standardised deployment reduces operator variability inherent to citizen sampling and ensures comparable air flow and turbulence conditions at each sampler location, thus reducing sampler bias (Meysman et al., 2020). Additionally, the real-estate panels generate street-level visibility of the project and create a community feeling among participants (“together we’re conducting a large science experiment”).

1.2.2 Execution of measurements

Sampling kits were distributed to participants via a parcel delivery service. PDTs were returned to the laboratory via the same service (using a return envelope included in the sampling kit). One to two week(s) before the start of the measurements, CurieuzenAir participants collected their sampling kit at a ParcelShop of their choice. The kit included two measuring PDTs, one real-estate panel and two cable ties to attach the passive samplers to the panel (in addition to an instruction manual and other information).

For optimal storage of the passive samplers, participants were asked to place the unopened PDTs in the fridge as soon as possible after collection of the sampling kit. To ensure proper installation of the tubes at all locations, the experimental setup was explained in a printed

[6] https://2016.curieuzeneuzen.be/
[7] https://2018.curieuzeneuzen.be/

manual (French, Dutch and English) included in the sampling kit and made available on the CurieuzenAir website. Additionally, a video manual was made available via e-mail explaining the different steps of the experimental setup.

Measurements started on 25 September 2021 at 13:00 (recommended time) and ended on 23 October 2021 at 09:00 (recommended time). Ambient NO_2 concentrations were hence monitored for a targeted period of 28 days (4 weeks). Some participants deviated from this recommended start and end times (e.g. schools and companies started and stopped one day earlier, from 24 September to 22 October). This poses no problem, since the actual start and end time is recorded and provided by the participants as metadata. The effective duration of the measurement period was used to calculate the NO_2 concentration (*1.2.3.2 Calculation of ambient NO_2 concentration*).

Participants opened the tubes by removing the yellow caps (Figure 5a). Two cable ties were used to attach the tubes to the inside of the measurement panel with the open side of the PDTs facing down (Figure 5b). The measuring panel was then attached to the window by removing the protective film from the mounting tape (Figure 5c) and sticking the board to the window (Figure 5d). During the measurement campaign, participants received a questionnaire via email at three points in time (i.e., start: 25 September, middle: 1 October and end: 23 October) requesting more detailed information about the measurement setup. This information included the actual start date/time, the actual end date/time, as well as the approximate height with reference to the street level. Participants were also asked to determine the exact coordinates of the measurement location using a Google maps application (initial coordinates were determined based on their street address (~10 meter uncertainty), and refined to ~ 2 meter uncertainty). They were also asked double check the serial numbers of the tubes to ascertain the correct connection between tube ID numbers with the measuring location.

At the end of the measurement period, passive diffusion tubes were closed with the same yellow caps (Figure 5e), put in the return envelope, and brought to the Parcelshop (Figure 5f). All tubes were sent to the University of Antwerp, where they were collected and sent to an accredited laboratory for analysis (this transport occurred on 18 November 2021). Tubes that were received after this date were not further analysed, as long-term transportation at sub-ideal temperatures could affect the results.

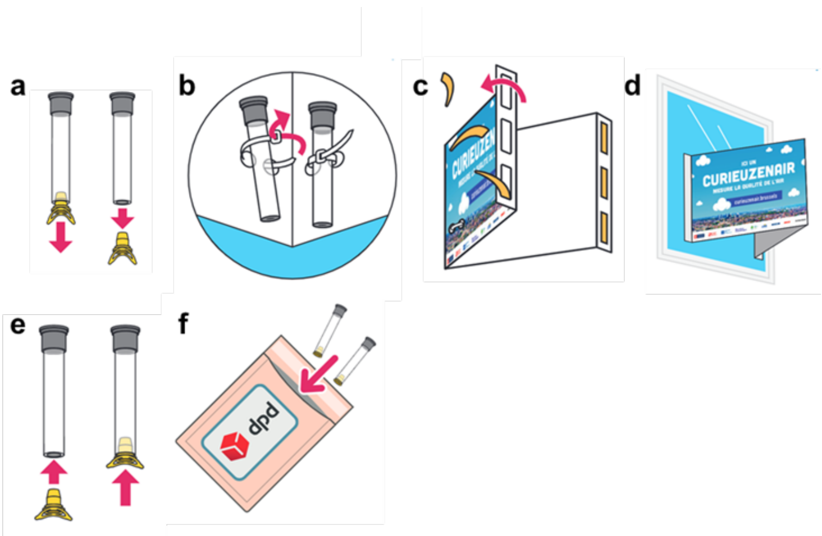


Figure 5. (a-f) Infographic from the CurieuzenAir manual showing the different steps in the installation and collection of the passive samplers (passive diffusion tubes) and (g) picture taken during installation at one of the participating schools. The CurieuzenAir measuring period lasted 4 consecutive weeks (25 September 2021 to 23 October 2021)

1.2.3 Palmes Diffusion Tubes

1.2.3.1 Working principle and analysis

Palmes-type diffusion tubes (PDTs; Palmes et al., 1976) were used to measure the ambient NO_2 concentration. Each tube consists of an acryl tube and a yellow and black cap (Figure 6). Inside the tube and at the level of the black cap, two stainless-steel meshes are placed coated with tri-ethanolamine (TEA), a selective adsorbent for $NO_{2,}$. The diffusion tube can be opened by removing the yellow cap, after which NO_2 from the atmosphere will diffuse through the tube and react with the TEA. In this reaction, ambient NO_2 is captured as nitrite (NO_2^-) on the tube meshes. High ambient NO_2 concentrations will hence result in higher diffusive fluxes and thus a higher mass of captured NO_2^-.

After the sampling period, NO_2^- will be extracted from the meshes using an aqueous solution after which the total mass can be determined by spectroscopy. The implemented sampling and extraction method and analysis follow the European Standard (DAN-03, equivalent to NEN EN 16339) for analysis of ambient NO_2 in a concentration range between 3 and 130 µg m^{-3} and with an exposure time varying from one to four weeks. Analysis was conducted in an independent and nationally accredited air quality lab (BuroBlauw, Wageningen, The Netherlands).

Figure 6. Infographic showing the different components of the Palmes diffusion tubes.

1.2.3.2 Calculation of ambient NO_2 concentration

From the measured NO_2^- mass in the sampling tubes, the ambient NO_2 concentration can be calculated using the mean air temperature (T) and atmospheric pressure (P) over the measurement period (t) (Equations 1). To account for possible effects of transport, NO_2^- masses measured in transport blanks (m_b) were subtracted from the masses measured in sample tube (m_s). Tube dimensions (cross area A; length L) are accounted for when calculating the retrieval speed θ (Equation 2). The NO_2 diffusion coefficient D depends on the mean air temperature over the measurement period (Equation 3; Heal et al., 2019).

$$C = \frac{m_s - m_b}{\theta * t} \frac{T}{T_{ref}} \frac{P_{ref}}{P}$$ Equation 1

$$\theta = D \frac{A}{L}$$ Equation 2

$$D = D_{ref} \left(\frac{T}{T_{refd}}\right)^{1,81}$$ Equation 3

With parameters:

C	Average NO_2 concentration over the measurement period	µg m^{-3}
m_s	Nitrite mass measured in sample tubes	µg
m_b	Nitrite mass measured in transportation blanks	µg
θ	NO_2 retrieval speed	m^3 s^{-1}
t	Measurement period	s
T	Average temperature	K
T_{ref}	Reference temperature	293 K
P	Mean atmospheric pressure	kPa
P_{ref}	Reference atmospheric pressure	101,3 kPa

D	Diffusion coefficient of NO_2	$m^2\ s^{-1}$
A	Area of the tubes	$8{,}17\ 10^{-5}\ m^2$
L	Length of the tubes	$7{,}85\ 10^{-2}\ m$
D_{ref}	Reference diffusion coefficient of NO_2 (at 298K)	$1{,}54\ 10^{-5}\ m^2\ s^{-1}$
T	Mean air temperature	K
T_{refd}	Reference air temperature	298 K

1.2.4 Meteorological conditions

Meteorological conditions were continuously measured at 30 min intervals in the reference station of Environnement Bruxelles (Quai de Mariemont, Molenbeek-Saint-Jean, 50°50'59.0"N, 4°20'02.8"E). Due to its location in the centre, measurements give a representative idea of the city's meteorological conditions. Mean T and P during the CurieuzenAir sampling period (i.e. from 25 September 13:00 to 23 October 09:00) were 12,81 ± 0,09 °C and 1016.29 ± 0,23 hPa, respectively (Figure 7). Some measurement locations experienced an earlier or delayed installation. To account for differences in mean T and P during the actual (location-specific) measurement period, mean meteorological parameters (T and P) were calculated for each individual measuring period per location.

Representativeness of the measured air quality during the four-week CurieuzenAir campaign, is largely determined by representativeness of the meteorological conditions during the four-week sampling period compared to those of entire year 2021. In particular, differences in wind speed or wind direction could give rise to a shift in wind-driven influx of external air pollution and thus a biased estimation of the annual average air quality at a specific location. During the year 2021 as a whole as well as during the four-week measurement period, the wind mainly originated from the south (S) and south-west (SW). Average wind direction was 186,15 ± 0,74° (S; mean ± standard error) and 201,26 ± 1,89° (S/SW; mean ± standard error) during the year 2021 and the four-week CurieuzenAir campaign, respectively. This hence suggests a slight deviation of the wind to the west during the CurieuzenAir period in comparison to the entire year 2021. Nonetheless, the wind roses composed for both periods (Figure 8; RStudio, *climaemet* package) show strong agreement in distribution of wind direction and speed between the two time periods. This indicates that the four-week measuring period was representative for the entire year 2021 and enabling us to make an estimation of annual air quality conditions in Brussels.

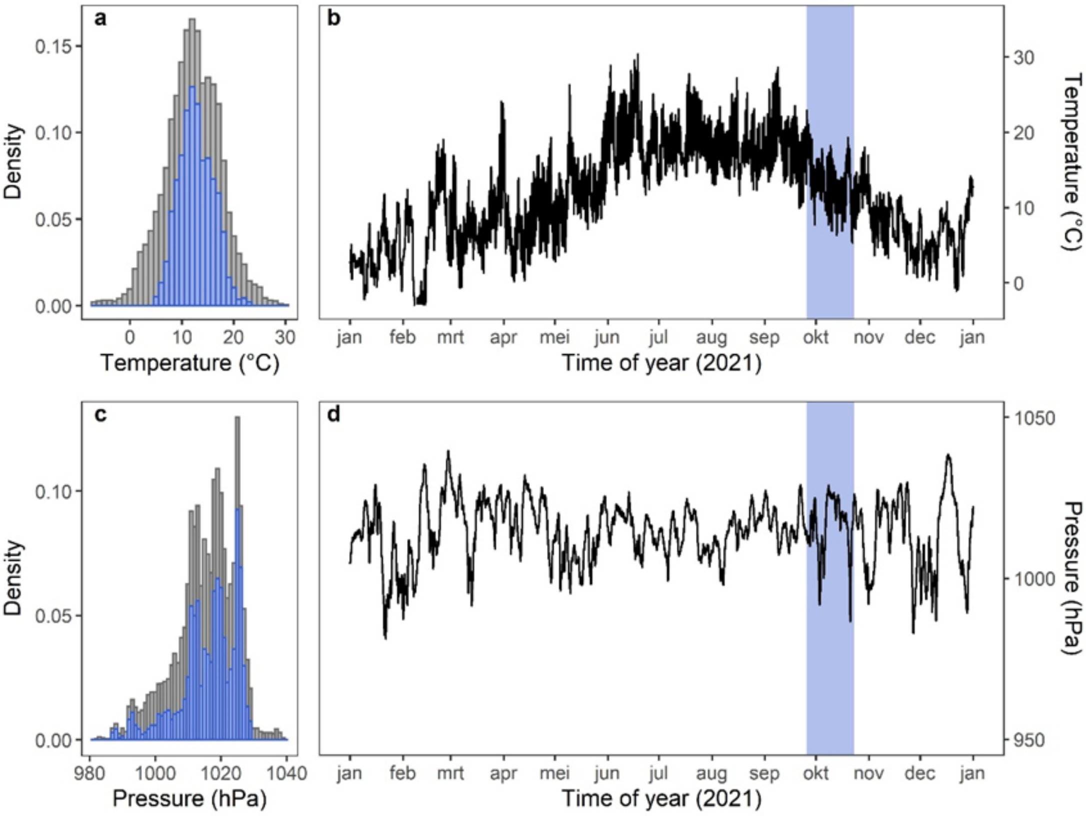


Figure 7. Air temperature and atmospheric pressure (30 min interval data) measured in the air quality reference station of Molenbeek-Saint-Jean (Environnement Bruxelles). Histograms show the air temperature (panel a) and atmospheric pressure (panel c) during the four-week CurieuzenAir measurement period (blue) and the entire year 2021 (grey). Line graphs show the temporal evolution of the air temperature (panel b) and atmospheric pressure (panel d) over the year 2021. The blue coloured periods in panels (b) and (d) indicate the CurieuzenAir measurement period.

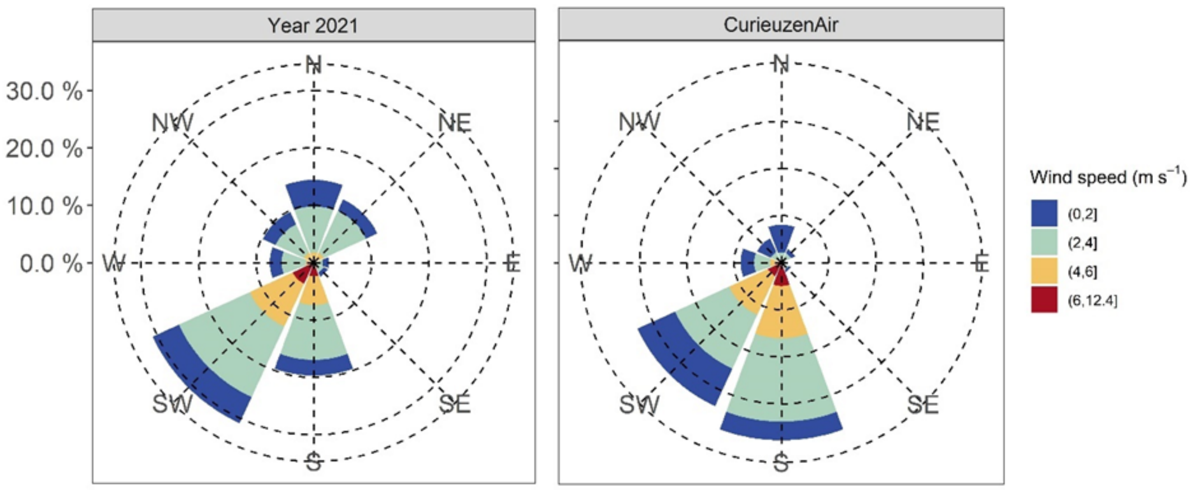


Figure 8. Wind rose graphs showing wind speed and wind direction during the entire year 2021 (panel a) and the CurieuzenAir sampling period (from 25 September to 23 October 2021; panel b). Wind speed and wind direction were measured at the air quality reference station of Molenbeek-Saint-Jean (50°50'59.0"N, 4°20'02.8"E; operated by Environnement Bruxelles).

Chapter 2: Data quality control

2.1 Transportation blanks

Transportation blanks allow us to determine if transportation affects the measured NO_2 concentration. Two types of transportation blanks were collected. A first set of diffusion tubes (n = 191) were directly set aside at the start of the measurement period, and hence not included in any sampling kit. These diffusion tubes were left unopened and stored in the fridge at the University of Antwerp. In addition to this, some sampling kits were not collected by the participants, and hence were sent back from the parcel shop to the University. These kits were opened upon return and the diffusion tubes were left unopened and stored in the fridge (n = 158). All these diffusion tubes were regarded as transportations blanks, enabling the assessment of possible transportation effects (from the lab to the University and back; or from the lab via the University to the Parcel Shop and back). After the measurement campaign, transport blanks were mixed with the actual sampling tubes (n = 6.000 – 158 = 5.842) to ensure random analysis.

Average NO_2^- mass from all the transportation blanks was 0,015 ± 0,003 µg (mean ± standard error). The transportation blanks showed clear outliers. For the calculation of blank mass (m_b in Equation 1) these outliers were removed. To this end, the valid mass range was defined as starting from the first quartile (Q_1) minus three times the InterQuartile Range (IQR) and ranging up to the third quartile (Q_3) with the addition of three times the IQR. Transportation blanks that fell outside this valid mass range were discarded, and the average NO_2^- mass in remaining tubes was determined as m_b= 0,007 ± 0,0003 µg (n = 276). This value for m_b was used in Equation 1 for the blank correction of the ambient NO_2 concentration. This value is significantly lower than the average NO_2^- mass of the sampling tubes (m_s = 0,897 ± 0,004 µg, mean ± standard error; $p < 0,01$).

2.2 Reproducibility of measurements

For each sampler tube, the raw (i.e., uncalibrated) NO_2 concentration was then calculated from the sampler mass m_s and the blank mass m_b via Equation 1. At each CurieuzenAir location two replicate diffusion tubes were installed in the tip of the measurement panel (Figure 5b). Large differences in measured NO_2 concentration values between these duplicate tubes can indicate sampler malfunctioning or contamination during one of the experimental stages (measurement, transport, analysis). Figure 9a provides the frequency distribution of the difference between duplicates, which provides a normal distribution. The Mean Absolute Error (MAE) gives a measure of the error between paired observations and is calculated as the mean of the absolute errors (i.e. the absolute value of the difference between the two replicate values). The MEA was 0,96 µg m^{-3} (Figure 9a). The Root Mean Square Error (RSME) provides an alternative error measure and was 2,4 µg m^{-3}. For comparison, the RSME in the CurieuzeNeuzen Flanders project amounted to 1,7 µg m^{-3}. The coefficient of variation (also referred to the relative standard deviation) was determined at the reference value of 40 µg m^{-3} (CV = 100*RMSE/40) and amounts to 6%. This value is comparable to previous studies and indicates that our passive sampler measurements show a good reproducibility.

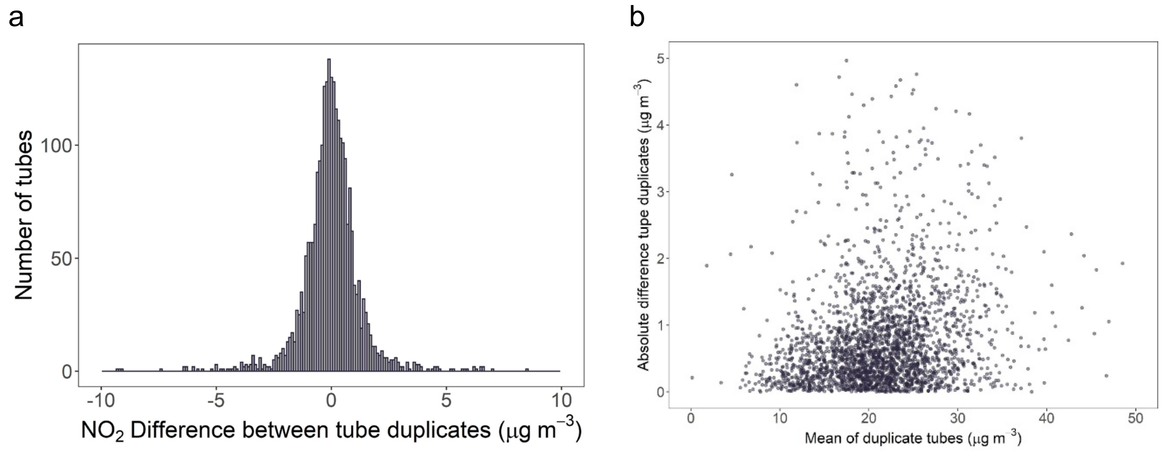


Figure 9. Reproducibility of NO_2 measurement. (a) Histogram with differences in measured NO_2 concentration between duplicate diffusion tubes at same location. (b) Differences between tube duplicates in relation to the duplicate mean (correlation = 0.15). NO_2 values depicted are raw (i.e. uncalibrated) NO_2 concentrations over the four-week period.

2.3 Outlier detection

The outlier detection procedure for the NO_2 concentration was similar as for the transportation blanks. We compared the duplicate measurements at each location and removed outliers based on a quantile regression. To this end, duplicate measurements were first log_2 transformed, and the difference between duplicates was regressed versus the duplicate mean (Supplementary Figure 1). The first and third quartile (Q_1 and Q_3) and interquartile range (IQR) of the difference between log_2 transformed duplicates was determined. Data points were considered outliers when the difference was either below Q_1 - 3 IQR or above Q_3 + 3 IQR (red markers in Supplementary Figure 1). In total n = 71 tube sets were removed after outlier detection. In addition, 10 CurieuzenAir locations were excluded from the dataset as only one of the tubes could be recovered (e.g. because a tube was lost or broke during measurements or transport). After removal of outliers, the MEA between duplicate tubes was 0,74 ± 0,01 µg m^{-3} and the Root Mean Square Error (RSME) decreased to 1,0 µg m^{-3}.

2.4 Final quality-controlled dataset

From the 3.000 selected and confirmed CurieuzenAir measurement locations, 2.739 CurieuzenAirs (or 91,3%) collected their sampling kit in the Parcel Shop. For

138 measurement locations crucial meta-data was missing, prohibiting the calculation of the exposure time and thus the ambient NO_2 concentration, and another 71 tube sets were excluded following the outlier detection (See *2.3. Outlier detection*). After lab analysis, 30 tube sets were excluded because various quality issues were observed on close inspection of the diffusion tubes: (1) reported damage to one of the tubes, (2) absence of a yellow closing cap, (3) observation of water inside the tube (likely result of installing the tube upside down), and (4) problems encountered during analytical measurement.

Measured NO_2 concentrations were then plotted on the map and inconsistencies in the spatial data were visually inspected. At three sampling locations, measured NO_2 concentration was in sharp contrast with all neighbouring sampling locations and hence they were therefore removed from the dataset. Overall, after quality control, 2.483 measurement locations were retained in the final dataset, representing 82,8% of the 3.000 confirmed CurieuzenAir locations (Table 2). These quality-controlled data points are also the ones that are plotted on the final “dotted map”. 89,01% of these measuring locations were private households, followed by companies and organisations (8,49%) and schools (2,49%).

Table 2. Overview of measurement locations that were retained in the final dataset.

	Number		Remaining	
	Absolute	**Relative to remaining (%)**	**Absolute**	**Relative of start value (%)**
Sent out to participants			**3000**	**100**
Not collected or late returned	261	8,7	2.739	91,30
Missing metadata	138	5,04	2.601	86,70
No duplicates	10	0,38	2.591	86,37
Difference between duplicate tubes outside of quality range	71	2,74	2.520	84,00
Measurement time too short	3	0,12	2.517	83,90
Measurement or analysis errors (Lab error, broken tube, missing cap, water)	30	1,19	2.487	82,90
Low values	1	0,04	2.486	82,87
Inconsistencies on dot map	3	0.12	2.483	82,77
Number of quality controlled CurieuzenAir locations			**2483**	**82,77**

After quality control, the CurieuzenAir locations remained representative for the whole population in the Brussels Capital Region. The dataset is geographically distributed out over the Brussels Capital Region (Figure 10a). A comparison of the histograms of the modelled NO_2 for the entire Capital Region and the CurieuzenAir locations show a good resemblance (Figure 10b). In agreement with the original 3.000 selected CurieuzenAir locations, the mean modelled NO_2 concentration at the 2.483 quality-controlled CurieuzenAir locations (27,7 ± 0,16 µg m^{-3}) remains higher than for the entire Brussels Capital Region (25,3 ± 0,01 µg m^{-3}).

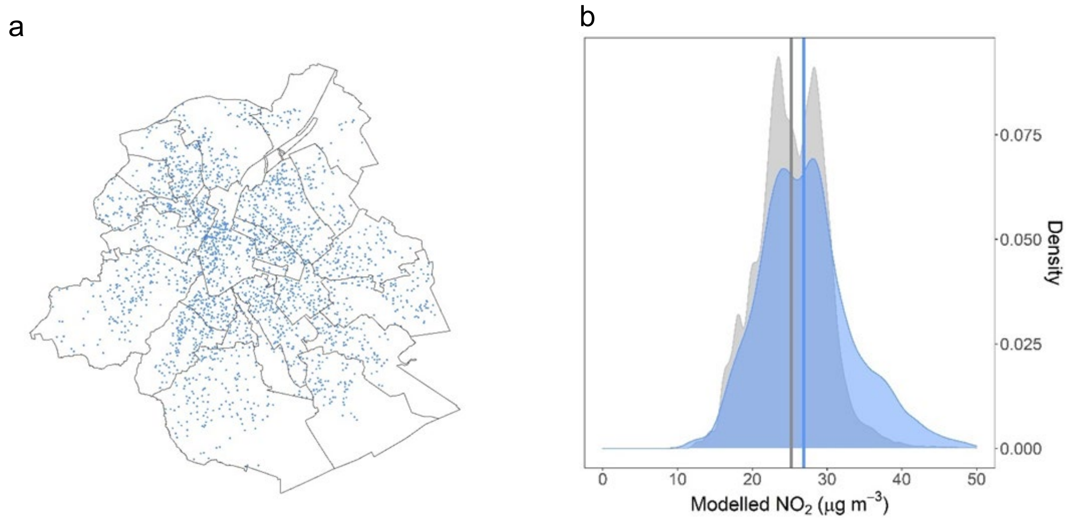


Figure 10. The quality-controlled dataset of CurieuzenAir includes 2.483 measurement locations. (a) Quality controlled CurieuzenAir locations plotted on the map of the Brussels Capital Region. (b) Frequency distribution of the modelled NO_2 concentrations at all quality controlled CurieuzenAir locations (blue, n = 2.483) and all street-level addresses in the Capital Region (grey; n = 224.996). Vertical lines indicate the median NO_2 concentration for the CurieuzenAir locations (blue) and that for all street-level addresses in the Capital Region (grey).

Chapter 3: Calibration

3.1 Comparison to reference measurements

Passive samplers are widely used for monitoring ambient NO_2 concentrations. Although Palmes diffusion tubes have been validated in numerous studies and results are comparable with those of certified reference measurements, diffusion tubes can show an intrinsic bias, as reviewed in Hafkenscheid et al. (2009). To detect and eliminate possible biases, CurieuzenAir measurement panels were installed at twelve reference stations during the four-week CurieuzenAir measurement period. The raw NO_2 values obtained from diffusion tubes were then compared to NO_2 value from the reference station (averaged over the period CurieuzenAir campaign), thus providing a calibration plot.

In the Brussels Capital Region ambient NO_2 is continuously monitored at ten reference stations managed either by Environnement Bruxelles (n = 8) or the European Parliament (n = 2). Reference stations are located in different municipalities with varying levels of urbanisation and traffic density levels (Figure 11 - inset). This enables reference air quality measurements that span the concentration range that is representative for the Brussels Capital Region.

To enable a proper calibration of the diffusion tubes, it is important that calibration plot contains enough data points and that it covers a wide range of NO_2 concentrations. To increase the number of reference points, two mobile reference stations were rented and installed (ISSeP, Liège - Belgium). They were stationed at locations where high NO_2 concentrations were expected (as indicated by simulated NO_2 concentrations from the ATMO-Street mode; over 2019). In collaboration with the VUB, one station was placed next to the of Boulevard General Jacques (50°49'23.7"N 4°23'30.0"E). A second mobile station was located at the Rue du Jardin Botanique (50°51'11.5"N 4°21'52.2"E) in collaboration with the SPF Sécurité Sociale. With addition of these two mobile stations, reference data was hence collected at n = 12 locations in total.

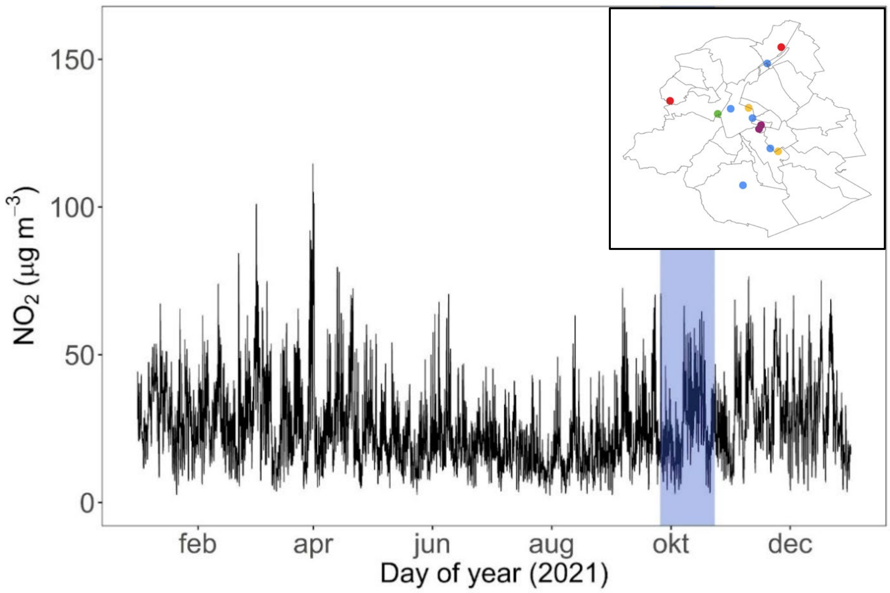


Figure 11. Evolution of the mean NO_2 concentration over the year 2021. Mean NO_2 is calculated as the average of 30 minute data measured by the n = 10 reference stations operational in the Brussels Capital Region operated by Environnement Bruxelles (n = 8) and the European Parliament (n = 2). The blue coloured period indicates the timing of the CurieuzenAir campaign. Inset = map of the Brussels Capital Region with the location of the reference stations. The green dot indicates the reference station of Molenbeek-Saint-Jean where climate and NO_2 data was collected. Blue dots = reference stations managed by Environnement Bruxelles. Purple dots = reference stations managed by the European Parliament. Orange dots = temporary mobile stations operated by ISSeP. Red dots indicate reference stations where passive sampling was unsuccessful due to detachment of the CurieuzenAir measurement panel; these stations were not used for calibration.

At each reference location, a set of two Palmes diffusion tubes was installed next to the air inlet of the reference station. At 10 locations a CurieuzenAir panel could be attached to the wall of the reference station. At the other two stations (i.e. Carrefour Arts-Loi (41B001) and Avenue de la Couronne (41R002)) it was not possible to install the panel in this way. Here the two diffusion tubes were placed in the same measurement cylinder as was used for the background concentration measurement (see above). At two reference stations, Berchem-Sainte-Agathe (41B011) and Neder-Over-Heembeek (41MEU1), the CurieuzenAir panel detached during the measurement period, disabling the collection of ambient NO_2 for at least 14 days (50% of the initial measurement period). As a result, only n = 12 - 2 = 10 reference locations provided suitable data for the calibration plot (Figure 11 - inset).

For each reference location, the averaged NO_2 concentration was calculated from the hourly data of the reference station over the CurieuzenAir measurement period. This reference NO_2 value was plotted against the sampler NO_2 value, i.e., the mean of the raw NO_2 concentrations obtained from the two replicate diffusion tubes (Figure 12a). A strong linear relation is obtained between the sampler data and the reference data (adjusted R^2 = 0,87). This shows that the low-cost CurieuzenAir setup enables a reliable estimation of NO_2 ambient concentration.

Three regression models were tested to establish a linear relation between sampler and reference data. The model with the lowest uncertainty was subsequently selected for calibration of the sampler data. This model procedure is documented in more detail in de Craemer et al., 2020.

Model a $y = a + x$
Model b $y = b*x$
Model c $y = a + b*x$

Regression was based on orthogonal regression (Deming regression with variance ratio 1). The model uncertainty was determined following a jackknife analysis. Model b showed lowest uncertainty (with standard error: 2,7 µg m^{-3} and coefficient of variation at reference value 40 µg m^{-3}: 6,8%). Equation 4 was used for the calibration of the raw passive sampler data, thus providing calibrated sampler values.

$$(NO_2)_{Calibrated} = \frac{1}{0,88}(NO_2)_{Raw\ sampler\ data} \quad \text{Equation 4}$$

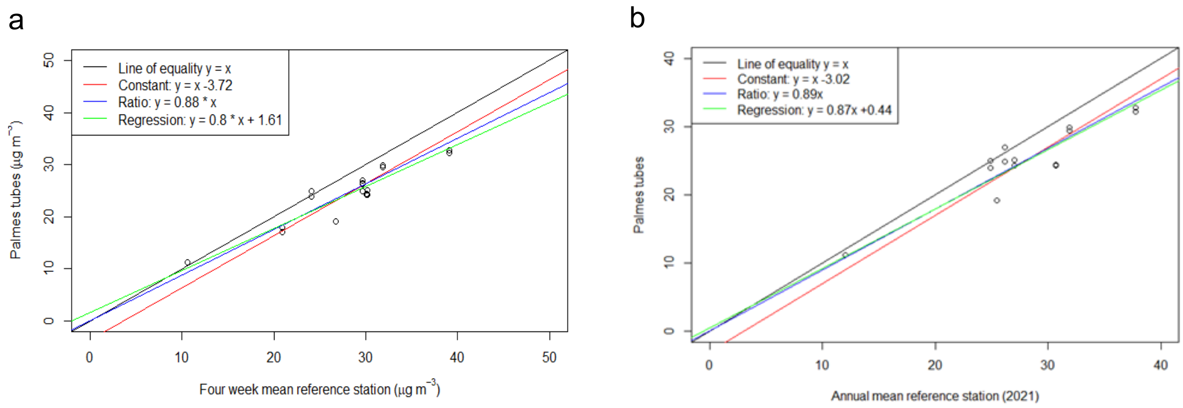


Figure 12. Linear regression models used for calibration and extrapolation of the passive sampler NO_2 data. (a) Comparison of the 4-week passive sampler data (25 September to 23 October 2021) to the averaged NO_2 concentrations from the reference stations over the same time period (n = 10 locations with available data). (b) Comparison of the 4-week passive sampler data (25 September to 23 October 2021) to the averaged NO_2 concentration from the reference stations over the whole year 2021 (n = 8 locations with available data).

3.2 Indicative annual NO_2 concentrations for 2021

The monitoring period for passive NO_2 samplers is restricted to 3-4 weeks in an urban context, in order to avoid that passive samplers become saturated. Therefore, the measurement period in CurieuzenAir was set to 4 weeks, and so, our calibrated NO_2 values essentially represent monthly averaged concentrations over October 2021. Compliance checking with guideline values of the World Health Organisation (threshold value of 10 µg m^{-3}; WHO, 2021) or limit values of the EU (threshold value of 40 µg m^{-3}; the Air Quality Directive, Directive 2008/50/EC) is however based on annual averaged NO_2 values. To enable compliance checking, it is therefore essential to convert the CurieuzenAir data (which are based on a four-week sampling period) to an indicative annual mean.

3.2.1 Statistical model

To this end, a normalisation procedure was recently developed (de Craemer et al., 2020), which reliably extrapolates the results of NO_2 passive samplers from multi-week averages to yearly averaged values. The central premise of this normalisation procedure is that air quality shows spatial synchrony: different sampling locations will show similar longer-term trends in NO_2 concentrations when these concentrations are averaged over multiple weeks. This implies that there is a high correlation between multi-week-averaged NO_2 values and annually averaged NO_2 values across sampling locations within a wider region (De Craemer et al., 2020). Detailed analysis reveals that NO_2 concentrations across Flanders indeed show suitable spatial synchrony (De Craemer et al., 2020). We expect a similar synchrony to hold across the Brussels Capital region (which is smaller than Flanders).

To build the normalisation model, we used again the NO_2 data collected from the reference stations, though now the annual mean NO_2 concentration was calculated from the hourly NO_2 data over the whole year 2021. This annual NO_2 value was now plotted against the sampler NO_2 value, i.e., the mean of the raw NO_2 concentrations obtained from the two replicate diffusion tubes (Figure 12b). Suitable data was available for n = 8 reference locations. Three separate statistical models were applied to relate the sampler data to the reference data: orthogonal regression, constant off-set and ratio multiplication - as specified by models (a-c). The model uncertainty (root mean square error) was calculated by the jackknife method as described above. The ratio model (model b) provided the model with lowest uncertainty (with standard error: 2,73 µg m^{-3} and a coefficient of variation at reference value 40 µg m^{-3}: 6,8 %). Equation 5 was used for the conversion of the raw sampling NO2 value to a corresponding indicative annual mean NO_2 concentration at all CurieuzenAir locations.

$$(\mathrm{NO_2})_{2021} = \frac{1}{0{,}89}(\mathrm{NO_2})_{\text{Palmes tubes}} \qquad \text{Equation 5}$$

Due to the importance of the annual mean NO_2 concentrations in health guidelines (WHO guideline) and existing legal framework (European Air Quality Directive), the indicative mean NO_2 value will be communicated to all participants and shown on the dotted map.

3.2.2 Uncertainty analysis

Air quality directives require that the uncertainty of measurements and model approaches is explicitly quantified. Quality objectives are typically expressed as the (expanded) relative uncertainty at the limit value of a given pollutant. More specifically, the EU air quality directive defines the model uncertainty as the maximum deviation between the measured and calculated concentrations for 90% of monitoring points and specifies that this uncertainty should be less than 30% for annual NO_2 values, defined at the reference value of 40 µg m^{-3}. Similarly, the data quality objective for indicative measurements via passive samplers is set at 25% for the same reference value.

To verify whether the CurieuzenAir approach meets the EU quality objectives, we quantified the uncertainty as the P95 value of the frequency distribution of the residuals (same approach as done in de Craemer et al., 2020). Assuming that errors are random and uncorrelated, we can combine the standard deviation of the passive sampler measurement (RMSE = 1,0 µg m^{-3} after outlier removal see *2.2 Reproducibility of measurements*) with the RMSE of the calibration towards annual values (2,7 µg m^{-3}; see above, section 2.1), to arrive at a total standard deviation of 3.7 µg m^{-3}. This then implies a relative uncertainty of u = 3,7*(100/40) = 9,3% at the reference value of 40 µg/m³, or equally, an expanded relative uncertainty u_{exp} = 1,645*u = 15% at the same reference value (where we adopt the correction factor 1,645 for the P95 quantile of the normal distribution). Accordingly, the indicative NO_2 values determined in the CurieuzenAir project satisfy the data quality objective for indicative measurements of the the EU air quality directive.

3.3 Estimation of long-term air quality evolution

Reference stations monitor the NO_2 concentration in great detail over time. A number of these stations are installed in Brussels (n=10 providing NO_2 data), and their location is chosen as to represent a range of typical emission environments. Still, one cannot directly assess the population exposure from the reference data, as one cannot link the reference stations to a proportion of home locations in Brussels. Because of this, one cannot evaluate how population exposure and exceedance of limits varies through time. The CurieuzenAir dataset has complementary properties compared to the reference data: the high spatial density of dataset brings representativeness (see *1.1.4 Representativeness of CurieuzenAir locations*), and hence it allows to assess population exposure and exceedance. However, the measurements are only collected at a single time point (October 2021).

We can however suitably combine the reference data and CurieuzenAir data to estimate to assess how population exposure and exceedance in the Brussels Capital Region have changed over the last two decades. To this end, we performed a similar statistical regression procedure as in Section 3.2 to generate indicative annual NO_2 concentrations for the years 2000 to 2020 (In addition to the already calculated 2021 values). The ratio model (Model b) was used to relate the NO_2 sampler values (October 2021) to the NO_2 reference values for individual years. This way, we obtained indicative annual NO_2 concentrations at all the 2.483 CurieuzenAir locations for each year between 2000 to 2020.

The mean NO_2 value at all CurieuzenAir locations shows a good correlation with the mean NO_2 concentration at the reference stations (Figure 16a). The fact the average concentration of all reference stations closely matches the average of all CurieuzenAir locations demonstrates that the monitoring network does a good job in tracking the “average air quality” in Brussels. No significant difference between the reference stations and CurieuzenAir values was detected during any year over the last two decades ($p > 0.1$).

Chapter 4
Air quality in Brussels

4.2The NO_2 dataset

4.2.1 Frequency distribution in 2021

The frequency distribution of the indicative mean NO_2 concentration for 2021 at all CurieuzenAir locations is shown in Figure 13 (n = 2.483, or 82,8% of the sampling kits). Results are subdivided in ten separate air quality categories, following the colour coding of the CurieuzenAir dotted map. Average NO_2 concentration in the Brussels Capital Region was 23.97 ± 0,14 µg m^{-3} (mean ± standard error).

NO_2 concentrations varied substantially across the Brussels Capital Region. The highest NO_2 concentration (60,5 µg m^{-3}) was measured at the Boulevard de Nieuport (Figure 13a). In the same street, at approximate 50 m distance, also the third highest NO_2 concentration was measured (52,6 µg m^{-3}), thus illustrating the consistency of measurements. The lowest concentration (6,2 µg m^{-3}) was measured in la Forêt de Soignes (Figure 13b). Even more, all ten lowest NO_2 concentrations (up to 7,4 µg m^{-3}) were measured at background locations in the same forest, thus again showing the consistency of measurements. The lowest NO_2 concentration in a residential area (7,6 µg m^{-3}) was measured in the Rue du Zenith (Berchem-Sainte-Agathe), and was likely a result of low traffic intensity due to the road works during the sampling period and consequent traffic diversions. The second lowest NO_2 concentration in a residential area (8,1 µg m^{-3}) was measured in Anderlecht (Rue Chant d'Oiseaux; Figure 13c).

Figure 13. Visualisation of CurieuzenAir locations. (a) Highest NO_2 concentration (60,5 µg m^{-3} Boulevard de Nieuport - Brussel). (b) Lowest NO_2 concentration overall (6,2 µg m^{-3}; Chemin des Tumuli, Forêt de Soignes). (c) Lowest NO_2 concentration in a residential area with no reported road works or traffic diversions (8,1 µg m^{-3}; Rue Chant d'Oiseaux - Anderlecht).

The frequency distribution of the measured NO_2 concentration at all CurieuzenAir locations (Figure 14) can be considered as the most important outcome of the CurieuzenAir campaign. As a result of the high number of quality approved measurements (n = 2.483) covering a large geographical area (Figure 10a) and with a representative NO_2 distribution for the entire Brussels Capital Region (Figure 10b), this frequency distribution is indicative not only for the CurieuzenAir participants, but also for all inhabitants of the Brussels Capital Region as a whole. As a result, this distribution allows us to make assumptions about the air quality to which all inhabitants of the Capital Region are exposed.

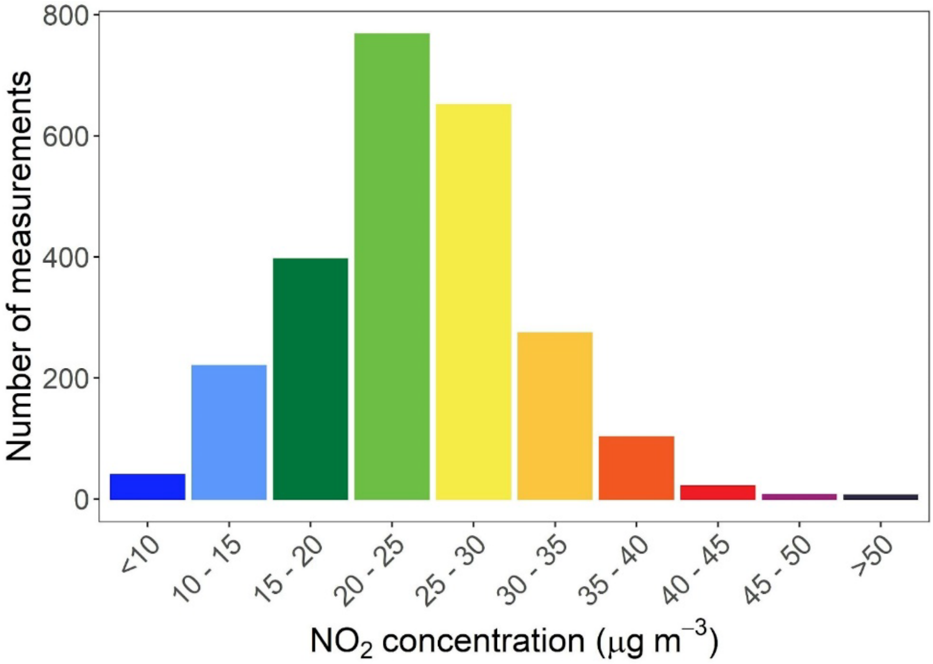


Figure 14. Frequency distribution showing the number of CurieuzenAir measuring locations for each NO_2 concentration category (n = 2.483 locations in total). The NO_2 concentrations displayed are the indicative annual mean NO_2 concentration for 2021.

4.2.2 Compliance and exceedance

4.2.2.1 The EU Air Quality Directive

To limit the impact of air pollution on health and strive for cleaner air in Europe, the European Union published the Air Quality Directive in 2008 (Directive 2008/50/EC). This directive provides the limiting values for different air pollutants, including NO_2, to which the population can be exposed. For NO_2, a limit value of 40 µg m^{-3} (average per calendar year) is put forward. This limit value had to be complied with by 1 January 2010.

The Brussels Capital Region did not comply with the rules of the Air Quality Directive on 1 January 2010. In effect, the EU limit for NO_2 was only first met for all reference stations in 2020 (Figure 15). As noted above, official monitoring networks are too sparse to verify whether the Air Quality Directive is truly met at all (home) locations within a given city or region. This is where large scale citizen science projects as CurieuzenAir show their added value: the high spatial density of measurement locations allows a representative sampling, which enables to verify whether the Air Quality Directive is met at the population level. In other words, the CurieuzenAir dataset allows to confidently estimate how many inhabitants of Brussels live at a location whether the EU threshold is exceeded.

The CurieuzenAir measurements show an exceedance of the EU limit at 1,37% of the measurement locations. Based on a total number of inhabitants of 1.219.970 (bisa) and assuming CurieuzenAir locations provide a representative distribution over the Brussels

Capital Region, this implies that approximately 16.714 inhabitants are currently living or working under circumstances where the EU norm is exceeded.

4.2.2.2 The WHO guideline

Over the past decade, new research on the impact of air pollution on health has revealed that NO_2 can already have health effects at lower concentrations than previously thought (i.e. well below 40 µg m^{-3}). For this reason, the WHO has updated its guidelines for ambient air quality in September 2021 (WHO, 2021). For NO_2, the WHO suggests lowering the annual limit to 10 µg m^{-3} (as this is the threshold concentration where health effects become apparent). As this limit concentration is today exceeded at almost all locations, intermediate step(s) are suggested, i.e., lowering the norm first from 40 µg m^{-3} to 30 µg m^{-3} or 20 µg m^{-3}.

The 'long-term' WHO guideline of 10 µg m^{-3} is only met at 1,6% of the CurieuzenAir locations, corresponding to approximately 19.642 inhabitants of Brussels. Table 3 indicates the percentage of CurieuzenAir locations and the corresponding number of inhabitants of the Capital Region that are exposed to different categories of NO_2 concentration as described by existing air quality limits (EU norm) and (possible future intermediate) WHO guidelines.

Table 3. Population exposure to NO_2 and exceedance of limit values. Absolute and relative number of CurieuzenAir locations within a specified NO_2 concentration category (10 µg m^{-3} intervals). The corresponding number of inhabitants is indicated for each category. Limit value described in the European Air Quality Directive (EU norm) and the guideline of the world health organisation (WHO guideline) are indicated.

		Absolute number of CurieuzenAir locations (-)	Relative number of CurieuzenAir locations (%)	Corresponding number of inhabitants (-)
≥ 40 µg m^{-3}	EU norm	34	1,4	16.714
30 - 40 µg m^{-3}		375	15,1	184.215
20 - 30 µg m^{-3}		1420	57,2	697.701
10 - 20 µg m^{-3}		614	24,7	301.698
< 10 µg m^{-3}	WHO guideline	40	1,6	19.642
Total		2.483	100	1.219.970

4.2.3 Historical evolution of air quality in Brussels

4.2.3.1 Historical evolution of the mean NO2 concentration

Continuous monitoring of the air quality at permanent reference stations allows an accurate evaluation of how NO_2 concentration evolves over time. Figure 15 plots the evolution of the annual NO_2 concentration at all reference stations in the Brussels Capital region over the period from 2000 to 2021. While there is variability between stations, in general, these references stations show the same overall trend. There is: (1) hardly any change between 2000 and 2010, (2) a gradual decrease in ambient NO_2 between 2010 and 2018, (3) a substantial and fast decrease over the period 2018-2020, and (4) a small rebound to higher concentrations in 2021 (Figure 12).

This temporal pattern can be adequately captured by tracking the average concentration across all reference stations in the Brussels Capital Region (the black dotted line in Figure 12). Before the proclamation of the European Air Quality Directive in 2010, the average NO_2 remained quasi stable, with a value of 39,2 µg m^{-3} in 2000, which only slightly decreased to 38,8 µg m^{-3} in 2010. Policy decisions subsequently resulted in a gradual improvement of air quality to 30,3 µg m^{-3} in 2019 (-21,9% in annual NO_2 over 2010-2019). From 2019 to 2020 the air quality improved spectacularly (-24,1% in annual NO_2, down to 23,0 µg m^{-3}), mainly attributed to a reduction in traffic intensity during the COVID-19 pandemic. As COVID-19 measures were reduced in 2021, NO_2 concentrations slightly increased again (+9,2%, from 23,0 µg m^{-3} to 25,2 µg m^{-3}; Figure 11). In 2021, the lowest value was measured in Uccle (reference station 41R012, 12,4 µg m^{-3}) and highest at the entrance of the Arts-Lois metro station (reference station 41B001, 37,8 µg m^{-3}).

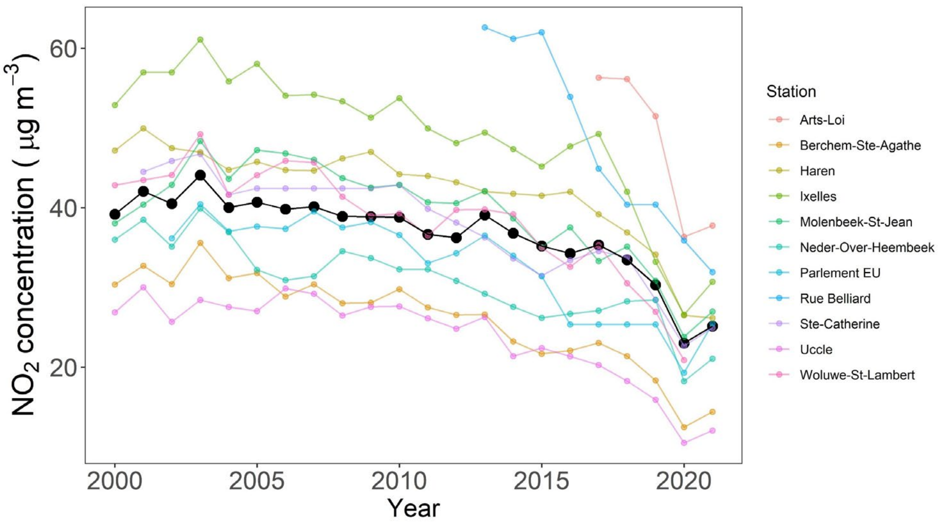


Figure 15. Historical evolution of the NO_2 concentration in the Brussels Capital region over the period from 2000 to 2021 based on data from the reference monitoring network. The annual NO_2 concentrations are indicated for individual reference stations (colored dotted lines). The black dotted line represents the average over all reference stations.

4.2.3.2 Historical exceedance of the EU norm

As noted above, air quality has substantially improved over recent years in the Brussels Capital Region. A suitably combination of the data from reference stations and the CurieuzenAir data allows to assess how population exposure and exceedance have also changed over the last two decades, i.e, to reconstruct frequency distributions. The principal assumption is that the overall shape of the frequency distribution remains invariant in time (while its parameters, like the media and variance can change).

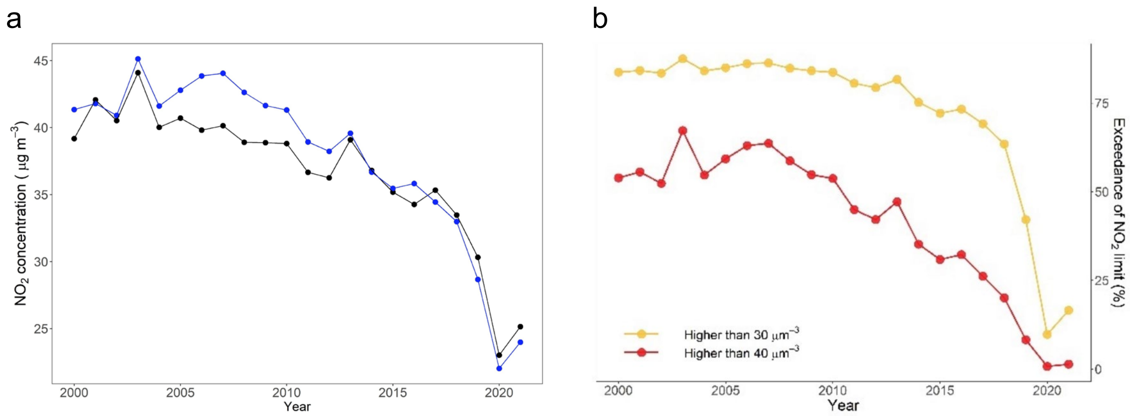


Figure 16. Historical evolution of the NO_2 concentration in the Brussels Capital region over the period from 2000 to 2021. (a) Evolution of the mean NO_2 concentration. Black dots show the mean NO_2 concentration across all reference stations. Blue dots show the mean of the indicative NO_2 concentrations at all CurieuzenAir locations in a particular year (normalisation of sampler NO_2 values for the corresponding year). (b) Time evolution of the exceedance above 30 µg m^{-3} and exceedance above 40 µg m^{-3}.

In agreement with the trend of the overall air quality in the Brussels Capital Region (Figure 15), the exceedance of the EU norm (> 40 µg m^{-3}) has substantially changed in recent years. During the period 2000-2100 exceedance was high and stable: over 50% of the population in Brussels lived or worked at a location where annual NO_2 was above the EU norm. For example, exceedance values up to 67% are estimated for in 2007 (corresponding with 666.850 inhabitants, when accounting for the population at that time). After implementation of Air Quality Directive, i.e. from 2010 onwards, the exceedance decreased gradually as air quality improved. In 2015, the exceedance had decreased to 30%.

In 2019, the last year before the start of the COVID-19 pandemic, EU norms were exceeded at 8,2% of the CurieuzenAir measurement locations (corresponding to 98.738 inhabitants. A sizeable reduction in traffic density in 2020 (as a result of the COVID-19 pandemic) lowered exceedance of the EU norm further to 0,7% (or 8.771 inhabitants), implying that nearly all the population of Brussels lived or worked at a location that satisfied the Air Quality Directive for NO_2. Yet, between 2020 to 2021, the relative exceedance increased again (up to 1,4%; Table 3) due to the partial recovery of the traffic intensity. The large differences in exceedance levels between 2019 and 2020 followed by the small increase in 2021 underlines the large effect of traffic intensity on air quality and therefore also on health.

4.2.4 Air quality near schools in Brussels

CurieuzenAir measurements were not only conducted at residential houses, but also at schools, companies and other organisations. From the 107 schools that subscribed and selected, 83 confirmed CurieuzenAir participation. After data quality control, data from 62 schools were retained. Figure 17 shows the locations of the 62 participating schools and the frequency distribution of the measured NO_2 concentration. At most schools (88%) the NO_2 concentration was within the 10 - 30 µg m^{-3} range (38% in the 10 - 20 µg m^{-3} range and 50% in the 20 - 30 µg m^{-3} range). In six schools (i.e. 10%) NO_2 concentration was high (30 – 40 µg m^{-3}) and for one school the EU norm was exceeded (47,8 µg m^{-3}). In one school the air quality was smaller than the WHO guideline of 10 µg m^{-3} (8,7 µg m^{-3}). For all schools, the average NO_2 concentration was 22.7 ± 0,9 µg m^{-3} (mean ± standard error).

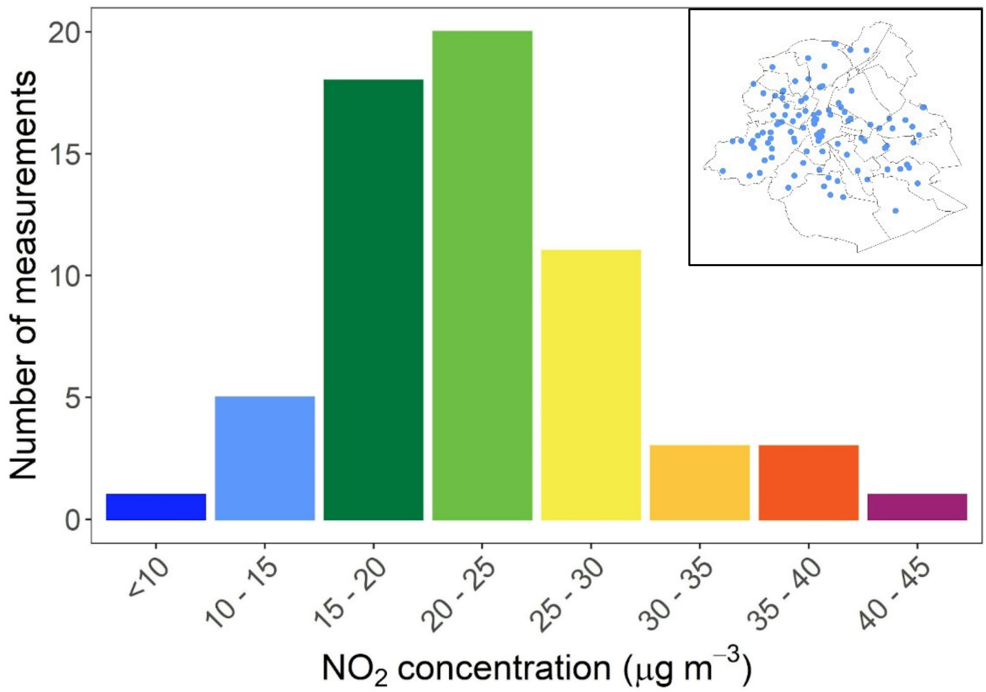


Figure 17. Frequency distribution showing the number of CurieuzenAir schools for each NO_2 concentration category. Inset shows the locations of the participating schools after data quality control. NO_2 concentrations indicate the indicative mean NO_2 concentration for 2021 (n = 62).

4.2.5 Comparison with Les Chercheur d'Air

In parallel with CurieuzenAir, the NGO Les Chercheurs d'Air (LCA) also conducted a citizen science project to document the NO_2 concentration at selected locations within the Brussels Capital Region. A similar setup was used, i.e., two PDTs measuring the NO_2 concentration for a four week period. In contrast to CurieuzenAir, LCA focussed on the temporal variability of the NO_2 concentration. To this end, NO_2 was measured for one year, from 30 October 2020 to 30 October 2021, at n = 134 locations. Passive samplers were replaced every four weeks. For each sampling location, the average NO_2 concentration of 24 measuring tubes (two replicate tubes for twelve consecutive months) was determined to assess the mean annual NO_2 concentration.

LCA results show strong similarities with CurieuzenAir results. In agreement with the CurieuzenAir results, most LCA locations had an annual NO_2 concentration between 20 and 30 µg m^{-3} (23,9%). Only two LCA locations (or 1,5%) exceeded the European norm of 40 µg m^{-3}. In contrast with CurieuzenAir, no locations with a mean annual NO_2 concentration below 10 µg m^{-3} were detected in Les Chercheurs d'Air. This is a likely the consequence of a selective bias in the measurement locations (skewed towards more highly polluted areas).

4.2.6 Filling the blank: air quality in Flanders and Brussels

In 2018 CurieuzeNeuzen measured the NO_2 concentration at 20.000 sampling locations in Flanders (Figure 18). The know-how gained from this large-scale citizen science project on air quality was used for the organisation of CurieuzenAir. The setup, i.e. two PDTs installed in the 'nose' of a real-estate panel, was identical, facilitating the comparison of the datasets.

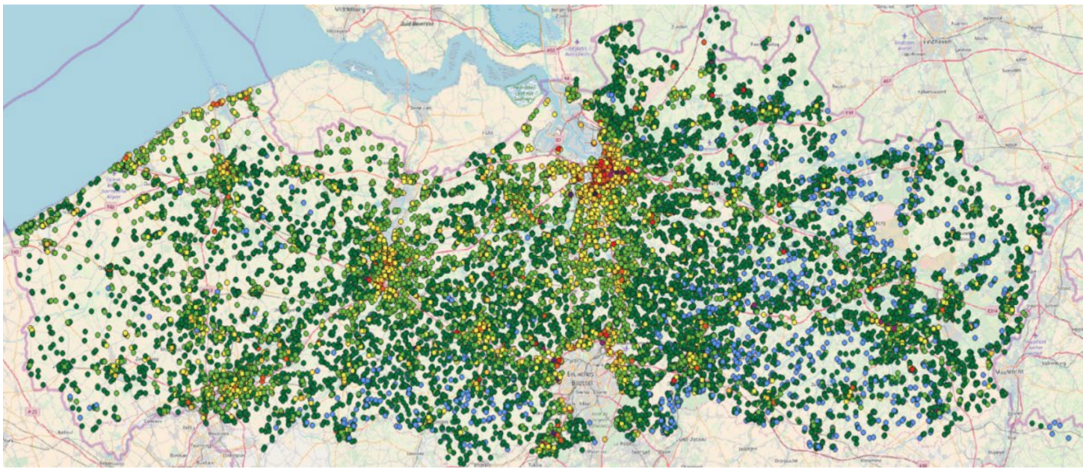


Figure 18. Dotted map with the measured NO_2 concentrations measured in the CurieuzeNeuzen campaign of 2018. NO_2 concentrations indicate the indicative mean NO_2 concentration for 2018. The interactive map with colour scale can be accessed via 2018.curieuzeneuzen.be.

In 2018, the mean NO_2 concentration in Flanders was slightly lower than the mean value in the Brussels Capital Region (i.e. 22,8 µg m^{-3} and 24,0 µg m^{-3} in Flanders and Brussels, respectively). Strikingly, maximal NO_2 in Flanders was higher than in Brussels (75,3 µg m^{-3} vs 60,5 µg m^{-3} in Flanders and Brussels, respectively), while minimal NO_2 was lower in Brussel than in Flanders (10,9 µg m^{-3} vs 6,2 µg m^{-3} in Flanders and Brussels, respectively). When comparing the relative exceedance of the EU norm, less values exceeded the EU limit in 2021 in Brussel (1,4%) compared to Flanders in 2018 (2,3%).

It is, however, impossible to use this data for a straightforward comparison of air quality between the two regions, as measurements were executed at different times. A first factor complicating comparison is that CurieuzenAir measurements were conducted during the COVID-19 pandemic, i.e, the year 2021 during which traffic and emissions were - at least partially – affected by telework regulations. As a result, long-term air quality data indicate a sharp improvement of the air quality in 2020 and 2021 in the Brussels Capital Region (Figure 15). Secondly, European cities have also addressed air pollution during the last three years. As a result of sustainable policy changes, high emission cars are banned from the city centre by introduction of low-emission zones and/or the number of cars is reduced with the introduction of pedestrian zones or circulation plans.

4.3 Spatial distribution of air quality of the Brussels Capital Region

4.3.1 Large-scale patterns in air quality across Brussels

The dotted map (Figure 19a) with the NO_2 concentrations shows a clear concentric pattern with increasing concentrations from the periphery to the city centre. Locations with NO_2 concentrations (indicative NO_2 values for 2021) smaller than 20 µg m^{-3} form a belt around the city centre (Figure 19b). The southern part of the Brussels Capital Region is characterized by open residential areas with a low population density, and this provides locations that fall within this < 20 µg m^{-3} category. Almost all locations with NO_2 concentrations smaller than 10 µg m^{-3} are located outside the outer ring road (R0). Lowest values are recorded at background locations within la Forêt de Soignes. Location within the 10 - 20 µg m^{-3} range are mainly located inside the outer ring road (R0), but outside the Petite Ceinture (smaller ring road around the city centre or Pentagon). Within the Petite Ceinture there is only one location with a mean annual NO_2 concentration under 20 µg m^{-3}: the centre of the Parc de Bruxelles (18,9 µg m^{-3}) at 160 m distance ('as the crow flies') of the nearest road.

The mid-range NO_2 category, which extends from 20 to 30 µg m^{-3}, is mainly detected in the transitional area between the outer city and the city centre (Figure 16c). NO_2 concentrations within the 20 to 25 µg m^{-3} range are found mainly outside the Pentagon, and only 17 of 768 sampling locations belonging to this NO_2 range are within the Pentagon. Sampling sites with high NO_2 concentrations (30 - 40 µg m^{-3}) and very high NO_2 concentrations (> 40 µg m^{-3}) are all found within or close to the city centre (Figure 16c). Still hotspots of high NO_2 are also detected outside the Pentagon, and as expected, these locations are found in close proximity to traffic dense streets (e.g. Petite Ceinture, Avenue des Gloires Nationales, Avenue Jacques Sermon, Rue Royale, Boulevard Lambermont and Avenue Louise).

The dotted map clearly shows the phenomenon of street canyons. One prominent example are the high NO_2 concentrations that are consistently detected in the Rue de l'Ecuyer and the Rue d'Arenberg (Supplementary Figure 2). These two streets, which form a continuation of each other, are located in the city centre and cross the pedestrian zone. At four locations along this road axis, the NO_2 concentration exceeds the EU norm (observed NO_2 values range from 40,2 to 51,0 µg m^{-3}). These high NO_2 concentrations are most likely caused by an interplay of the street geometry and dense traffic. Both streets are narrow and have high, terraced housing on both sides of the road. This street canyon architecture impedes the air circulation and therefore slows down the dilution of air pollutants emitted by the transit traffic. Air pollutants thus can pile up to high concentrations in these street canyons.

The effect of traffic density on air quality becomes clear when comparing these measurements with two neighbouring sampling sites. At the intersection of the Rue de l'Ecuyer and the Boulevard Anspach, NO_2 concentrations were markedly lower and ranged within the 25 – 30 µg m^{-3} range (26,9 µg m^{-3} and 28,9 µg m^{-3}). This local improvement of air quality can likely be attributed to the fact that the Boulevard Anspach and neighbouring streets have been designated a pedestrian area, thus lowering the local NO_2 emissions.

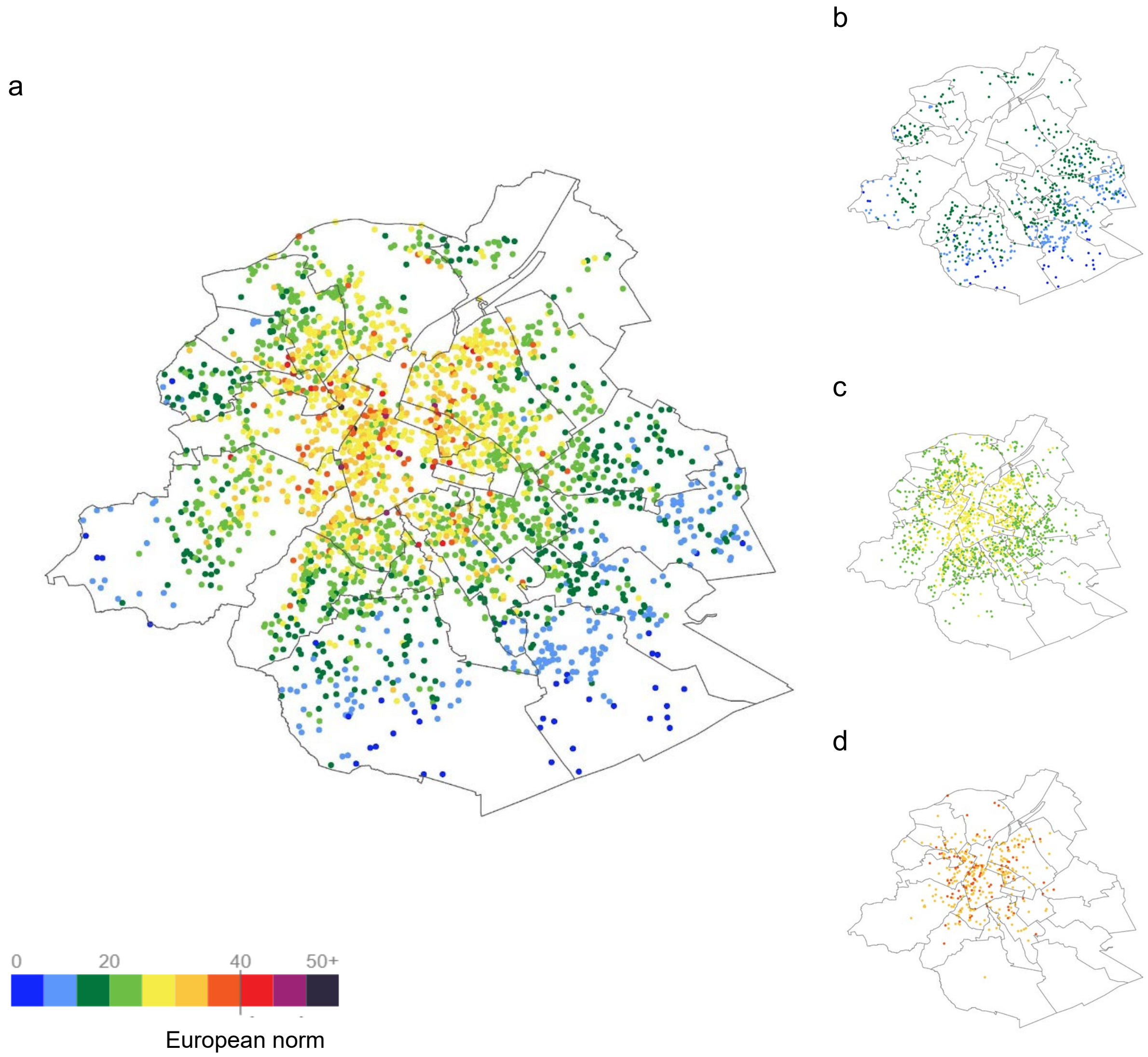


Figure 19. Dotted map showing the mean annual NO_2 concentration for 2021 at all CurieuzenAir locations (n = 2.483). (a) Overview map of all locations. (b) Locations < 20 µg m^{-3}, (c) Locations between 20 - 30 µg m^{-3}, and (d) locations ≥ 30 µg m^{-3}.

4.3.2 Long-term spatial distribution of NO_2 in the Brussels Capital Region

Figure 20 shows how the spatial pattern of NO2 evolves as the air quality improves between 2010 to 2020. In 2010, NO_2 concentrations were high in a large part of the Brussels Capital Region, providing a map that is dominated by red and black dots (Figure 16a). The EU limit (40 µg m^{-3}) is surpassed in the city centre at the majority of locations, while low NO_2 concentrations (< 20 µg m^{-3}) limited to the extreme southern part of the capital region.

The gradual decrease in the mean Brussels-wide NO_2 concentration from 2010 to 2015 (Figure 16a), also resulted in a reduction of the 40 µg m^{-3} exceedance levels (Figure 16b). As a result, in the region between the Pentagon and the outer ring, NO_2 concentrations decreased to just below the EU limit (Figure 20 – Year 2015). As a result of the more substantial air quality improvements from 2015 to 2019 (Figure 16a), NO_2 concentrations reduced both inside and outside the Brussels' Pentagon. From 2019 onwards, locations where the EU limit was surpassed were limited to the Pentagon and locations close to high dense traffic roads (Figure 20 – Year 2019). The unprecedented reduction in traffic intensity during the COVID-19 pandemic resulted in a corresponding substantial improvement of the air quality. Inhabitants of the Pentagon particularly benefited from these air quality improvements (Figure 20 – Year 2020). Exceedance levels (> 40 µg m^{-3}) were lowered to 0,72% and exceedance locations were limited to the traffic dense roads and street-canyons.

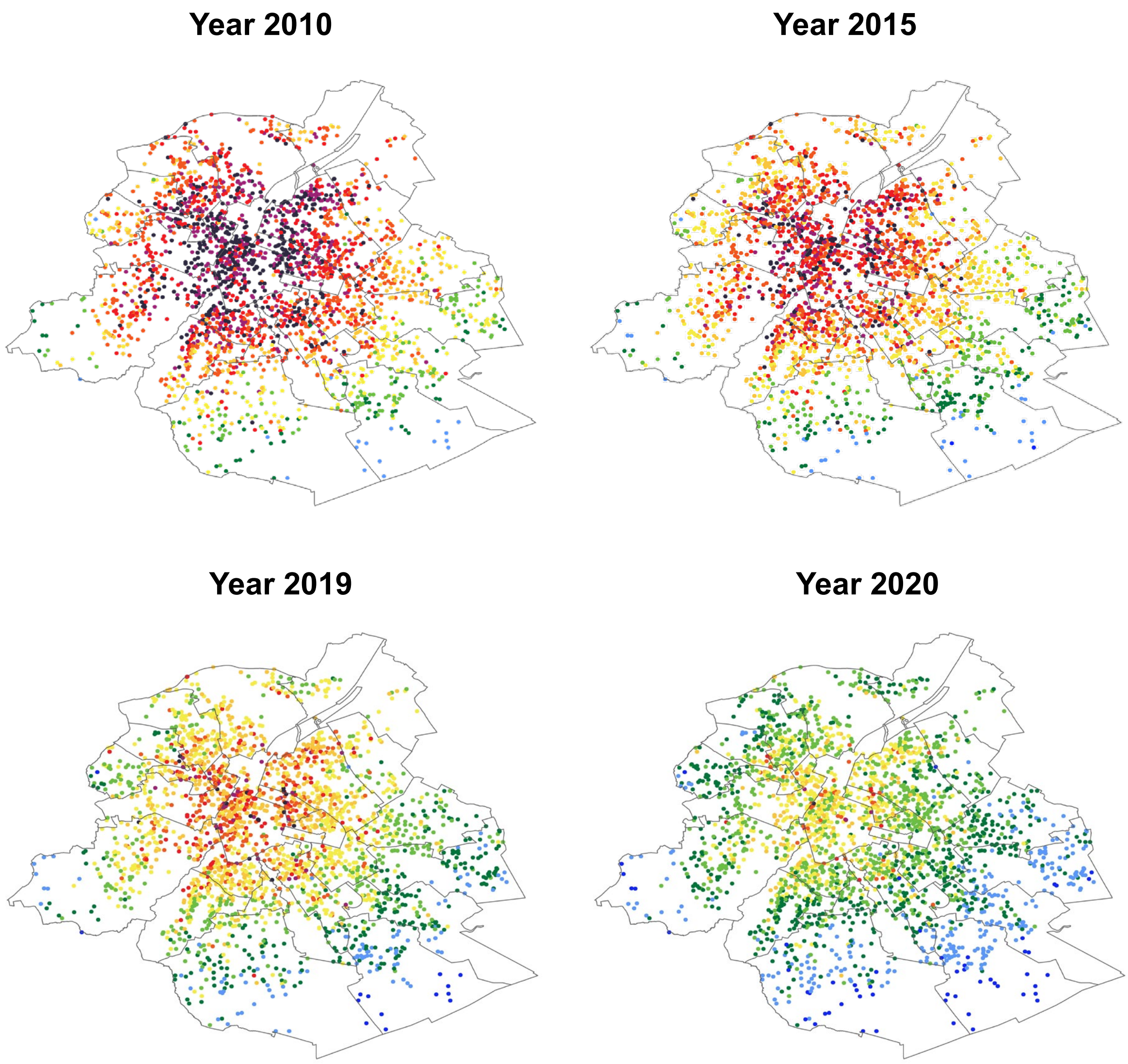


Figure 20. Reconstruction of how air quality has improved the Brussels capital region over the period 2010-2020. NO_2 concentrations are estimated based on CurieuzenAir data for 2021 and historical data from the refence monitoring network. The dotted maps show the mean annual NO_2 concentration in 2010, 2015, 2019 and 2020 at all CurieuzenAir locations (n = 2.483). Applied colour coding of concentration classes correspond to the colour scale in Figure 19.

4.3.3 Differences between and within municipalities

The observed increase in ambient NO_2 concentration from the periphery to the city centre is also reflected in the mean NO_2 concentrations for the nineteen municipalities of the Brussels Capital Region (Figure 21, Supplementary Table 1). Lowest mean NO_2 concentrations at the municipal level were detected in Watermael-Bosvoorde (12,6 µg m^{-3}), Woluwe-Saint-Pierre (15,7 µg m^{-3}) and Auderghem (16,9 µg m^{-3}). These three municipalities are all located in the green belt south of the city centre. In contrast, municipalities with the highest mean values were Saint-Josse-ten-Noode (31,0 µg m^{-3}), Molenbeek-Saint-Jean (29,4 µg m^{-3}) and Koekelberg (28,4 µg m^{-3}). Two out of these three municipalities (Saint-Josse-ten-Noode and Molenbeek-Saint-Jean) border the Petite Ceinture. Although Koekelberg is located outside the geographic centre, the high traffic density associated with the R20 pushes the mean NO_2 concentration upward to the third highest of the Brussels Capital Region.

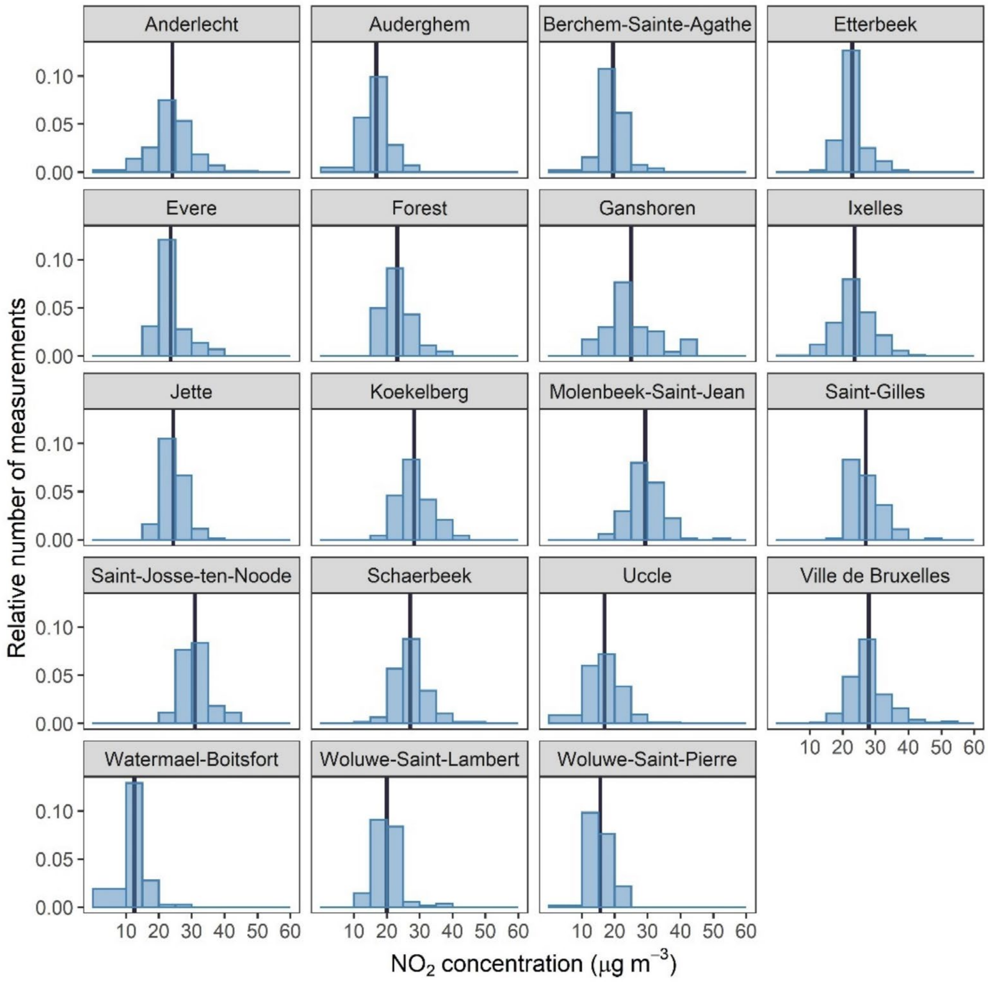


Figure 21. Frequency distributions indicating the relative number of CurieuzenAir locations over the different NO_2 concentration categories for all nineteen municipalities in the Brussels Capital Region. Black line indicates the mean NO_2 concentration within the municipality. The indicated NO_2 concentrations refer to the indicative mean NO_2 concentration for 2021.

In addition to differences between municipalities, there are also some noteworthy differences in the NO_2 concentration range (i.e. difference between maximal and minimal measured NO_2 within a single municipality; see Figure 21 and Supplementary Table 1). For most municipalities the NO_2 range varied between 20 and 30 µg m^{-3}. However, in Woluwe-Saint-Pierre the difference between the highest and lowest NO_2 concentration was only 15,2 µg m^{-3}. This suggests a more homogeneous distribution of air pollution over the entire municipal area. Largest NO_2 ranges were detected in Ville de Bruxelles (range = 48,4 µg m^{-3}; from 12,1 µg m^{-3} to 60,5 µg m^{-3}) and Anderlecht (range = 41,1 µg m^{-3}; from 8,1 µg m^{-3} to 49,2 µg m^{-3}). This wide NO_2 range can be attributed to the large area covered by these municipalities, stretching from the low polluted areas near the border of the Brussels Capital Region to the high concentrations near the Petite Ceinture (Anderlecht) and in the city centre (Ville de Bruxelles).

4.3.4 Strong variation in NO_2 concentration over small distances

The CurieuzeNeuzen Flanders (2018) campaign showed that air quality is largely dependent on local emission conditions, meaning that the NO_2 concentration can greatly vary over very short distances.

Also in the Brussels Capital Region, some areas show sharp NO_2 gradients. One of these locations is the Boulevard Bischoffsheim (City of Brussel; Figure 22a). Here, the measurement location with the second highest NO_2 concentration in the entire Brussels Capital Region was encountered (52,3 µg m^{-3} and 54,3 µg m^{-3}). Nonetheless, only a few streets away, in the area surrounding the Place des Barricades, all NO_2 concentrations are within the 25 – 30 µg m^{-3} range. When comparing the two sampling sites closest to each other (Boulevard Bischoffsheim and Rue des Cultes), a difference in NO_2 concentration of 24,9 µg m^{-3} was observed over an approximate distance of only 30 m (hence a gradient of 0.8 µg m^{-3} per meter). This clearly underscores the local differences in air quality can be substantial and depend strongly on the intensity of local emissions and local ventilation patterns.

A similar NO_2 gradient can also be observed in proximity of traffic-free zones. In the neighbourhood of the Parc de Bruxelles, the NO_2 concentration decreased 21,5 µg m^{-3} over a distance of only 250 m (or 0,09 µg m^{-3} per meter; Figure 22b). In the Rue du Régent, the NO_2 concentration was high at 40,4 µg m^{-3}, but decreased to 18,9 µg m^{-3} in the centre of Parc de Bruxelles. This gradient is further supported by different measurements in the Rue de la Loi, which show intermediate concentrations (24,9 to 26,7 µg m$^{-3)}$. A third example is the ULB campus La Plaine (Figure 22c). At the campus entrance (junction of three dense traffic roads), the NO_2 concentration was high (39,8 µg m^{-3}). Yet, in the centre of the university campus, where car traffic is not allowed, the NO_2 concentration was almost 20 µg m^{-3} lower (19,3 µg m^{-3} providing a gradient 0,09 µg m^{-3} per meter).

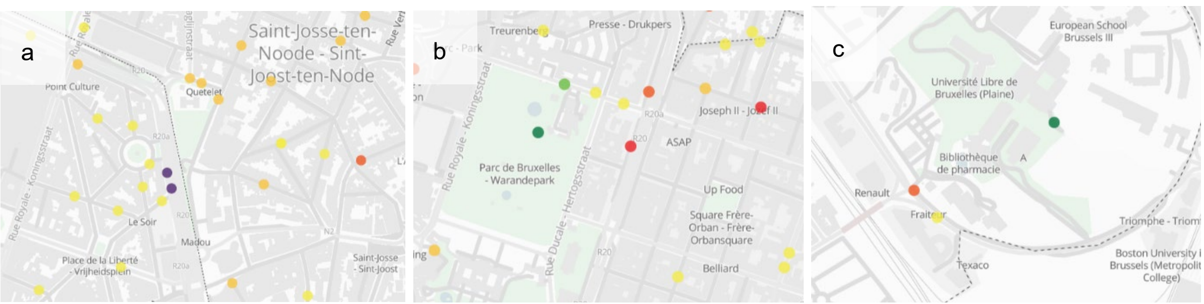


Figure 22. The dotted map reveals strong gradients in NO_2 concentrations over very short distances. Panels zoom in at three locations in the Brussels Capital Region. (a) Boulevard Bischoffsheim, (b) Parc de Bruxelles, and (c) ULB campus La Plaine (ULB). Dots show the indicative mean NO_2 concentration for 2021. The colour legend for the measurement locations is the same as in Figure 19.

Chapter 5: Air (in)quality

5.1 The Brussels' neighbourhood monitor

The high spatial resolution of the CurieuzenAir dataset allows correlation of air quality with socio-economic variables. Previous studies have shown that in urban settings, lower social class households are more likely to live in areas of poor air quality, with a concomitant impact on their respiratory health (Deguen & Zmirou-Navier, 2010; Wheeler, 2005). To examine whether there is a link between air pollution and socio-economically disfavoured areas in the Brussels Capital Region, the CurieuzenAir NO_2 data (regrouped according to neighbourhood) were connected to socio-demographic data on neighbourhoods as supplied by the *Monitoring des Quartiers*[8].

In 2005 the Brussels Capital Region developed the *Monitoring des Quartiers*, an interactive instrument providing data on 145 neighbourhoods in Brussels: 118 residential areas (99,7% of all inhabitants live there), 6 industrial areas (or stations), 18 green zones and 3 cemeteries. Figure 23a shows the location of the CurieuzenAir sampling locations while Figure 23b shows the location of the residential areas of the *Monitoring des Quartiers*. As can be observed in Figure 23, there is a good coverage of the residential areas of the Brussels Capital Region by the CurieuzenAir project. There are measurement results for all 118 residential areas with on average 21 measurements per neighbourhood.

The reader should, however, be cautioned that working with aggregated data for this type of analysis has its limits. Air quality and NO_2 pollution can vary greatly between neighbouring streets and even within the same street due to local variation in traffic density, street morphology and the presence of trees (*4.3.3 Strong variation in NO_2 concentration over small distances*). It is hence therefore challenging to compare air quality across neighbourhoods. One hence should not simply presuppose homogeneity as there can be important gradients in air quality within neighbourhoods. We should keep this in mind when we look at correlations between averages air quality results for neighbourhoods and their socio-demographic characteristics. Note that the latter can also vary in important ways within neighbourhoods. Nevertheless, taking this caveat into consideration, it is interesting and important to examine patterns that interconnect air quality and socio-demographic characteristics of neighbourhoods.

[8] https://monitoringdesquartiers.brussels/

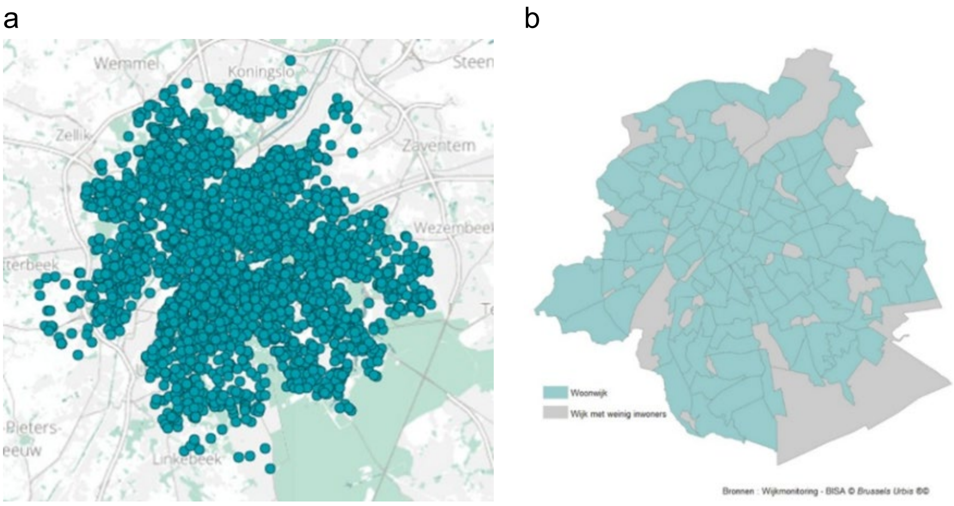


Figure 23. Map of the Brussels capital region with indication of the (a) CurieuzenAir measuring locations and (b) surface covered by residential neighbourhoods (Monitoring des Quartiers).

5.2 Patterns of urban inequality reflected in the air quality map

There are clear spatial patterns in the CurieuzenAir air quality data, with the lowest NO_2 values observed in the South-Eastern part of Brussels, while the highest NO_2 values are found in the 19th century belt around the historical centre of Brussels and along the Canal. Visual inspection of the CurieuzenAir dotted map (Figure 24a) and comparison with other maps of the Brussels Capital Region reveal several striking patterns, reflecting both the characteristics of the built environment as well as longstanding sociological cleavages.

In Figure 24b we find a map of population density of neighbourhoods in 2020. In blue coloured neighbourhoods the population density is high, in green coloured neighbourhoods it is low. Figure 24c provides a map with the median taxable income in 2018. Blue coloured areas are richer, green coloured neighbourhoods are poorer. The pattern is clear: more densely populated neighbourhoods tend to be poorer. These are also the neighbourhoods where the average age of inhabitants is lower and the concentration of inhabitants of foreign non-EU origin is the highest (Jacobs & Swyngedouw, 2000). The north-west / south-east divide, sometimes also referred to as the difference between the lower and upper city, has deep geohistorical roots and goes back to the patterns of urban development in the 19th Century (Wayens et al., 2010). Over time, there have been some changes due to urban renewal programs, processes of gentrification, shifts in median income levels (Hermia & Treutens, 2021) and upward social mobility of non-EU-origin migrant groups. However, the broad patterns have over the last decades roughly remained the same. By comparing these maps, we can clearly observe that there is also an important overlap between the demographic and socio-economic divide on the one hand and air quality on the other hand (Noël et al., 2020).

The spatial pattern in socio-economic inequality is also reflected in Figure 24d, which focusses on child poverty. This figure shows the proportion of minors that live in a family or household, which does not receive an income from work. In the green coloured areas, the proportion of child poverty is relatively low. In blue coloured neighbourhoods, the percentage of children who live in a family that has no income from work is higher. The darker the blue colour, the more child poverty in the neighbourhood. The north-west / south-east divide is once again clear.

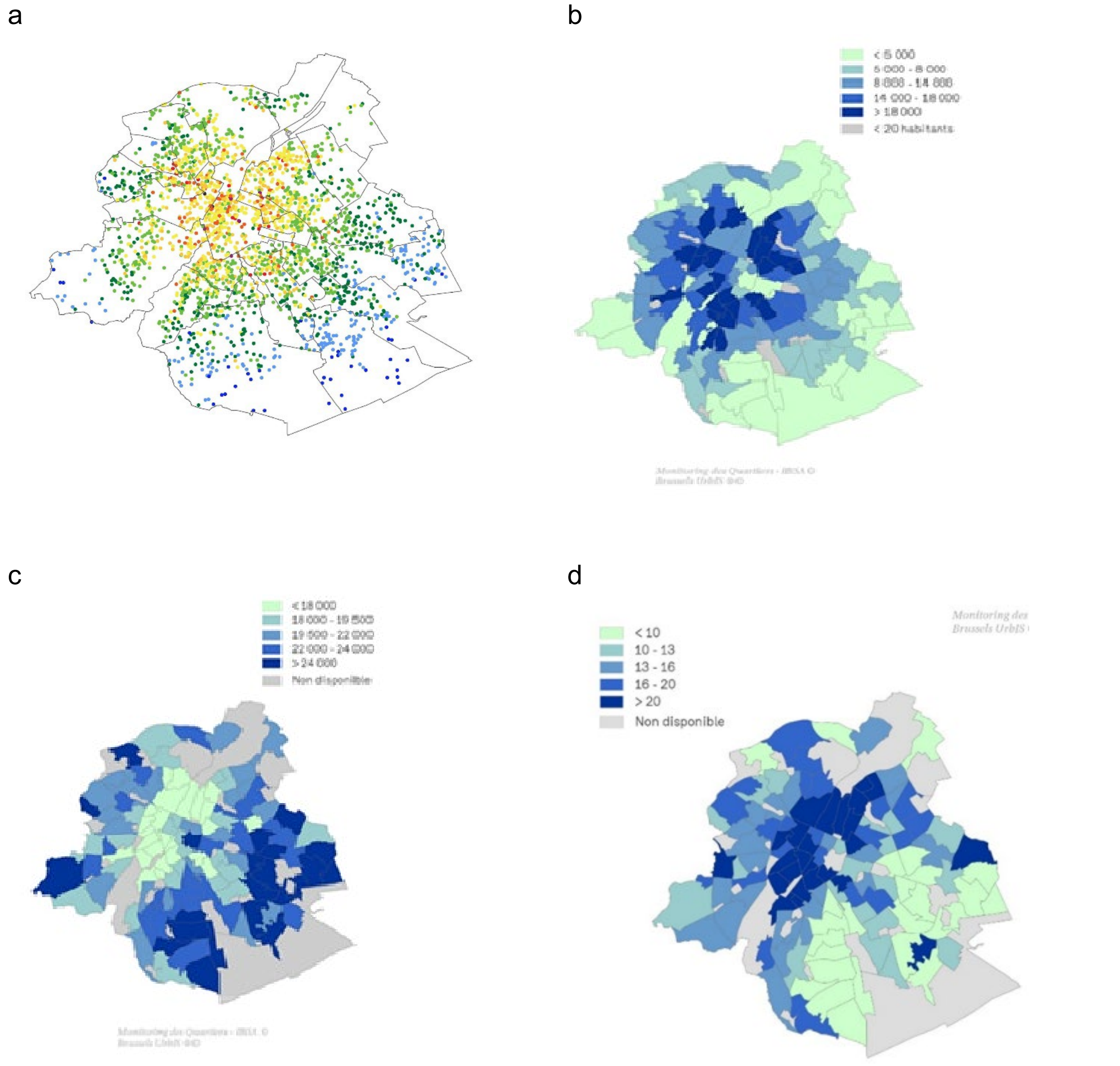


Figure 24. Air quality and socio-economic factors across neighbourhoods in The Brussels Capital region. (a) NO_2 concentration at the CurieuzenAir sampling locations (for colour coding of the concentration scale see Figure 16), (b) Population Density per neighbourhood (Stabel 2020 & IBSA, Monitoring des Quartiers, Brussels UrbIS). (c) Median Taxable Income per neighbourhood (Statbel 2018 & IBSA, Monitoring des Quartiers, Brussels UrbIS). (d) Proportion of children in a family without income from work in 2016 (BCSS & IBSA, Monitoring des Quartiers, Brussels UrbIS).

5.3 Air quality in relation to socio-economic variables

5.3.1 Analysis at the level of neighbourhoods

The CurieuzenAir data were aggregated in the same form as the socio-economic data (i.e., as an average concentration per residential neighbourhood). Figure 25 presents the histogram of the NO_2 per neighbourhood. Typically, a Brussels residential neighbourhood tends to have a score between 20 to 30 µg m^{-3}. 14 neighbourhoods have a score between 10 to 15 (11,9%), 16 fall in the range 15 to 20 (13,6%), 43 are to be found in the range 20 to 25 (36,4%), 31 fall in the range 25-30 (26,3%) and 13 have a score between 30 and 35 (11%). All of the 118 residential neighbourhoods show an average NO_2 concentration below the European norm of 40 µg m^{-3}. Note however that this applies to neighbourhood averages and not to individual locations surpassing the EU limit. Indeed, 19 residential areas (and one non-residential area) do contain measurement locations that exceed the EU norm.

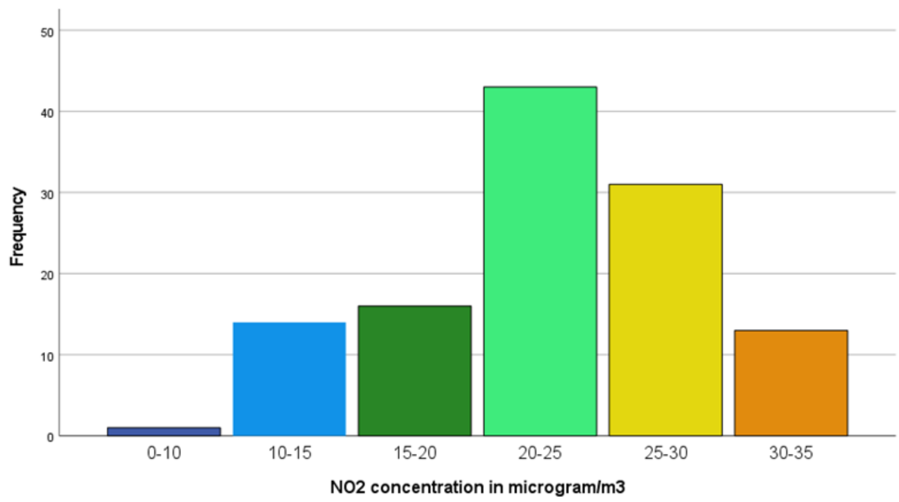


Figure 25. Frequency distribution of the mean NO_2 concentration within the n=188 neighbourhoods in the Brussels Capital Region.

We can furthermore observe a strong overlap between indicators of socio-economic characteristics of neighbourhoods (as tracked by the Monitoring des Quartiers) and the CurieuzenAir air quality results. As can be seen in Figure 26a, there is a good correlation ($r = 0,660$, $p<0,001$) between population density of a neighbourhood and the average CurieuzenAir score for NO_2. Neighbourhoods with a higher population density hence tend to experience higher air pollution levels. Also, there is a strong negative correlation ($r = -0,670$, $p<0.001$) between the median taxable income (2018) and the NO_2 data for neighbourhoods: the poorer the neighbourhood, the worse the air quality is (Figure 26b).

Not surprisingly, additional significant correlations are found between air quality and indicators such as the percentage of unemployed ($r = 0,623$), the youth unemployment rate ($r = 0,572$) or the proportion of minors living in a family without work related income ($r = 0,572$). This is no surprise as all these socio-economic variables are correlated among each other, since they are all indicators of how poor or how rich the inhabitants of a given neighbourhood are.

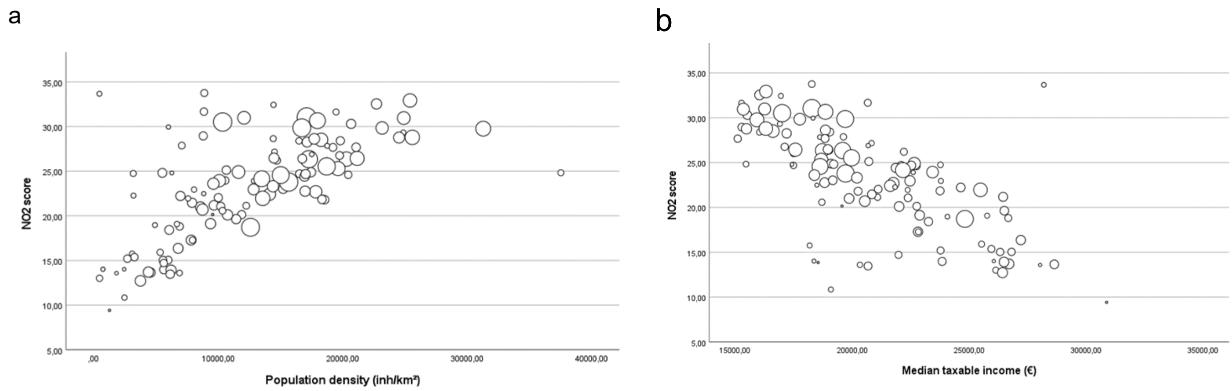


Figure 26. Scatterplots demonstrating the correlation between mean NO_2 concentration per neighbourhood and socio-economic factors. (a) Air quality versus population density (b) Air quality versus median taxable income per neighbourhood. The size of the points reflects the number of measurement locations per neighbourhood.

5.3.2 Zooming in to the level of statistical sectors

As highlighted before, there can be important variability in air quality and socio-economic variables within neighbourhoods. Therefore, it is important to also perform a more fine-grained analysis of the results, and aggregate the data at the level of so-called statistical sectors. CurieuzenAir data are available for 565 of the statistical sectors across the Brussels Capital region. However, caution is necessary here: statistical sectors contain fewer measurement locations compared to neighbourhoods and within statistical sectors there can be substantial variation in air quality from one location to another. Hence, aggregation in terms of statistical sectors is more prone to unwanted biases and errors resulting from small sample size.

At the level of statistical sectors, the correlation between the car ownership and measured NO_2 concentration was examined (Figure 27; $r = -0{,}662$, $p<0{,}001$). Statistical sectors with a higher level of car ownership (per household) tend to have better air quality levels, while statistical sectors with less car ownership tend to have higher levels of pollution. Ironically enough, a counter-intuitive pattern emerges. Air quality issues related to NO_2 pollution, mainly stemming from traffic, are clearly more present in neighbourhoods where households own less cars or where households do not have a car.

What we are observing is a spurious relationship. Air quality is worse in densely populated and poorer areas, where people have less cars. The reason for this is both financial (cars are costly) as well as practical. Even though the inhabitants of these sectors have less cars in comparison to other places in Brussels, there still are a lot of traffic emissions and hence pollution. In addition, in these statistical sectors there are less ‘low-pollution’-areas (e.g. parks or squares) to mitigate the effect of air pollution. Furthermore, in densely populated parts of the city there will be a more frequent presence of so-called street canyons (relatively narrow streets with buildings lined up continuously on either side).

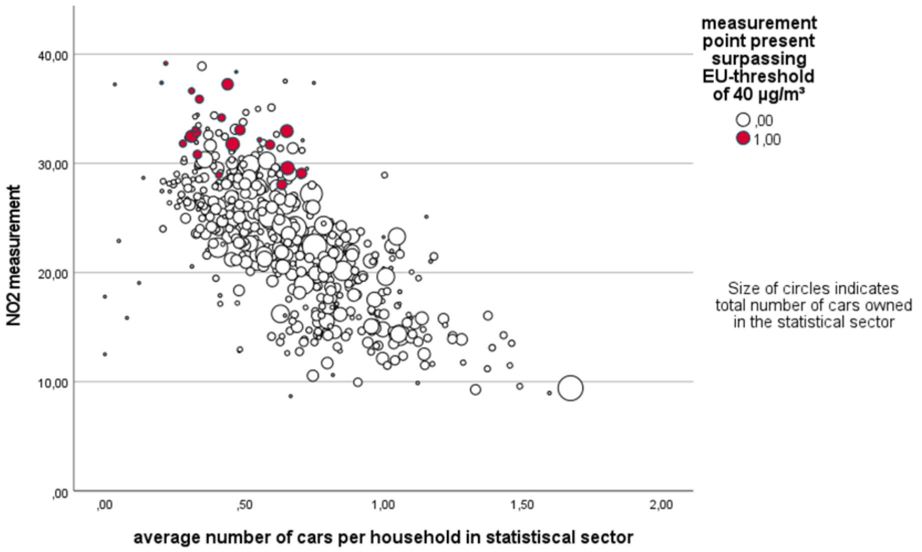
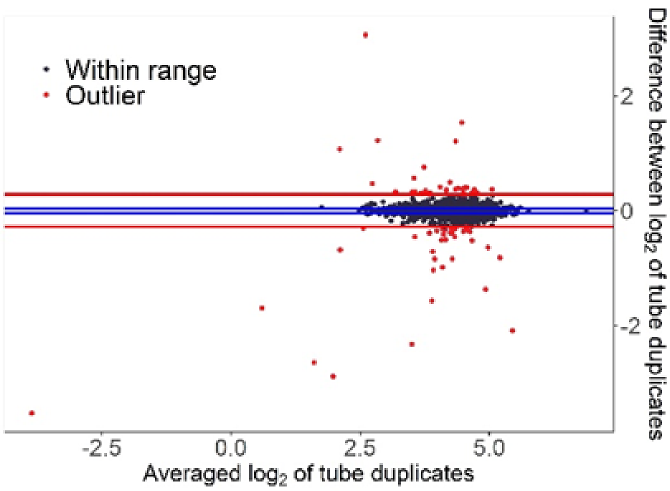


Figure 27. Scatterplot of the average number of cars per household (2019) and the mean NO_2 level per statistical sector. The size of the points reflects the number of cars owned per statistical sector. Statistical sectors for which at least one measurement point surpasses the EU threshold for NO_2 (40 µg m^{-3}) are indicated in red.

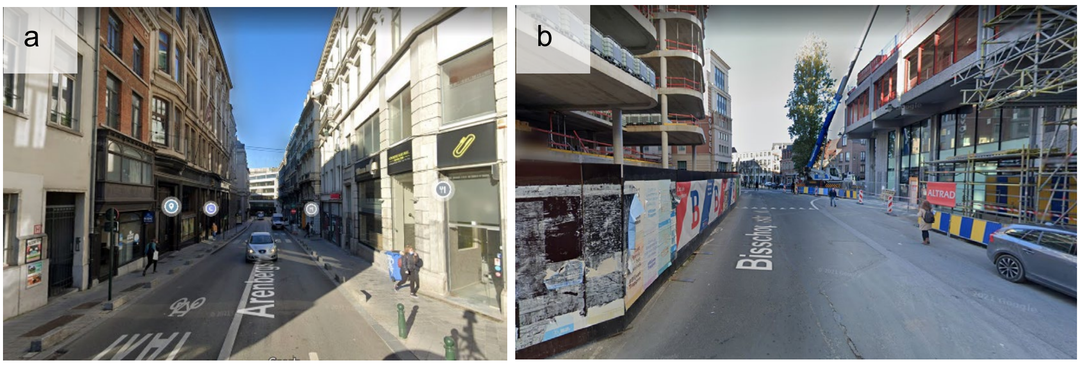
Supplementary data

Supplementary Table 1. Mean NO_2 concentration with standard error and minimal and maximal measured NO_2 concentration, for all municipalities. NO_2 concentrations show the indicative annual mean for 2021 and are calculated based

Municipality	NO_2 (µg m^{-3})	se (µg m^{-3})	Lowest NO_2 (µg m^{-3})	Highest NO_2 (µg m^{-3})
Anderlecht	24,15	0,46	8,12	49,19
Auderghem	16,87	0,43	7,38	27,95
Berchem-Sainte-Agathe	19,51	0,53	7,66	34,24
Etterbeek	22,95	0,38	12,63	35,89
Evere	23,62	0,60	15,84	37,91
Forest	23,27	0,41	15,92	37,54
Ganshoren	25,01	1,12	14,18	44,42
Ixelles	23,67	0,42	8,1	41,57
Jette	24,42	0,31	17,76	38,38
Koekelberg	28,38	0,70	19,85	40,63
Molenbeek-Saint-Jean	29,36	0,43	18,87	50,75
Saint-Gilles	27,02	0,45	19,19	45,48
Saint-Josse-ten-Noode	31,01	0,63	23,16	44,43
Schaerbeek	27,14	0,31	10,07	47,85
Uccle	16,92	0,42	7,31	35,98
Ville de Bruxelles	27,92	0,28	12,13	60,50
Watermael-Boitsfort	12,65	0,38	6,21	29,00
Woluwe-Saint-Lambert	20,04	0,37	13,75	37,50
Woluwe-Saint-Pierre	15,66	0,30	9,43	24,67



Supplementary Figure 1 Differences in log_2 transformed NO_2 concentrations in relation with the averaged log_2 NO_2 concentration measured in tube duplicates. Blue and red lines indicate the range defined by the first (Q_1) and third (Q_3) quartile and the applied outlier range ($Q_1 - 3\ (Q_3 - Q_1)$ and $Q_3 + 3\ (Q_3 - Q_1)$). Red points show the tube sets where differences in NO_2 concentration between tube duplicates was outside of the outlier range. These tube sets were excluded from the dataset.



Supplementary Figure 2 Picture of (a) Rue d'Arenberg and (b) Rue de l'Ecuyer in the City of Brussels. In these two streets, which form a continuation of each other, NO_2 concentrations surpassed the EU norm of 40 µg m^{-3}. High NO_2 concentrations are most likely caused by an interplay of the street geometry (narrow streets with high terraced housing on both sides of the road) and dense traffic.

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