

Large-scale citizen science provides high-resolution nitrogen dioxide values and health impact while enhancing community knowledge and collective action

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Abstract

We present outcomes from a large-scale air quality citizen science campaign (xAire, 725 measurements) to demonstrate its positive contribution in the interplay between advances in exposure assessment and developments in policy or collective action. A broad partnership with 1,650 people from communities around 18 primary schools across Barcelona provided the capacity to obtain unprecedented high-resolution NO₂ levels and an updated asthma Health Impact Assessment. It is shown that NO₂ levels vary considerably with at some cases very high levels. More than a 1,000 new cases of childhood asthma could be prevented each year by lowering NO₂ levels. Representativity of site selection and the minimal number of samplers for land use regression modelling are considered. Enhancement of community knowledge and attitudes towards collective response were observed and identified as key drivers for successful large-scale monitoring campaigns. The results encourage strengthening collaboration with local communities when exploring environmental health issues.

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Introduction

Outdoor air pollution causes 4.6 millions premature deaths worldwide [1] each year and 400,000 premature deaths in Europe, and contributes significantly to cardio-vascular diseases, asthma, allergies, strokes or impediments on cognitive development [2–6]. Guideline values established by the World Health Organisation (WHO) are very often exceeded by one or multiple air pollutants in urban areas worldwide [1]. Nine out of 10 people live in areas above the WHO guidelines.

Among the existing air pollution indicators, nitrogen dioxide (NO_2) concentration level is considered a key value to evaluate air quality in urban areas, due to its relationship with motor vehicles with internal combustion engine emissions [7]. According to the European Environment Agency [2], around 7% to 8% of the Europeans living in urban areas, about 25 million people, were exposed to high or very high levels of NO_2 concentrations between 2015 and 2017 (above $40 \mu\text{g}/\text{m}^3$). Exposure to high concentrations of NO_2 results in a broad range of environmental health impacts [1], especially affecting vulnerable groups such as elder and younger inhabitants, and causes for instance childhood asthma [8–10]. Motorized traffic is a main contributor (around 70-80%) to NO_2 levels in cities such as Barcelona (Spain). Barcelona is a compact city that has a very high vehicle density (approx. 9,525 vehicles per km^2), and the majority of passenger cars are diesel (65%) [11, 12]. It is also estimated that at least 48% of Barcelona inhabitants are exposed to high NO_2 concentration levels [13].

In 2017, the annual concentrations of NO_2 in Barcelona captured by the two existing traffic automatic monitoring stations were 59 and $52 \mu\text{g}/\text{m}^3$ [13], both above the $40 \mu\text{g}/\text{m}^3$ WHO and European Commission (EC) limit values [2, 14]. This noncompliance with air quality recommendations has been systematically reported for several years [15]. It is also well documented that NO_2 concentration levels can show strong variations, from one street to another, and thus individual citizen’s exposure to air pollution can also vary depending on the location he/she lives, studies or works [16–19]. However, the distribution of official air quality stations that comply with EU Legislation [20] is not dense enough to obtain complete or high-resolution data for any city [21–27]. For instance, in Barcelona in 2019, there were only seven NO_2 air quality monitoring automatic stations (as mentioned, two urban traffic stations in densely populated areas and five urban background stations [13] for a 101 km^2 area, with 1.636.762 inhabitants [12]). The low number of NO_2 air quality

automatic monitors can limit in several ways a robust understanding of air pollution exposure distribution in cities such as Barcelona, and especially when this data is expected to be used to translate air quality levels into health impacts and policy [21].

In terms of public awareness, a recent opinion poll in European cities showed air pollution as the issue of most concern for citizens after climate change [28]. However, a majority of respondents did not feel well-informed about air quality problems in their country, and only around one third of respondents had heard of the European air quality standards. Even with this lack of information, respondents were more likely to think that air quality has deteriorated (58%) over the past ten years, even though the opposite occurred, and that the EC should propose additional measures to address air quality-related problems in Europe (71%). Finally, 38% of the respondents would like to be able to express their own views on this issue.

Citizen science practices provide a way to actively and collectively respond to air quality issues [29]. Citizen science, broadly defined as the participation of the public in research [30, 31], offers methods to gather massive data and accelerate data processing while elevating public awareness, knowledge, and understanding about scientific methods and the societal relevance of science outcomes [32]. There are already a wide range of disciplines and topics that are obtaining significant outcomes thanks to active public involvement in scientific research [33, 34]. However, the more popular citizen science is, the more diverse and ambitious it has become, thanks to its interplay between research, society and policy making [35–44]. Recent articles illustrate how crowdsourced citizen science data can elucidate opportunity costs and large spatiotemporal representations including: conservation efforts of fisheries [45], migratory birds species [46], biodiversity in general [47, 48], mosquito and other organisms control from a public health perspective [49–51], human mobility patterns [52] or earthquake locations [53]. These examples, among others, consider and evaluate collective spatial coverage and mapping in one way or another.

For air pollution, citizen science is generally using low-cost sensors. Indeed, connectedness low-cost sensor technologies [54–61] are helping to improve air quality monitoring, transparency, awareness and action between citizens and authorities [62–64]. Cities [55, 65] and public agencies [29] are also beginning to share their environmental exposure data and in some cases to introduce participatory frameworks [66]. Worldwide, nonprofit organizations [67], public health or environmental agencies [29], and even self-organised groups are indeed

developing citizen science strategies for the interplay between advances in environmental exposure assessment and developments in policy [55, 64, 65, 68, 69]. Opportunistic mobile monitoring campaigns are one possible strategy to gather high-quality resolution data [70]. These campaigns make use of existing mobile infrastructures and people’s common daily routines to deploy measurement devices, for example, with the participation of city employees to measure black carbon [71] or determining burden of disease by adding passive sensing of human mobility using cellular phone signals [72]. Other initiatives enhance their impact on participant’s knowledge and attitudes [73, 74] and untap the potential of incorporating citizens and local communities in research processes [75].

The CurieuzeNeuzen citizen science project in Antwerp (517,000 inhabitants), promoted by a group of experts, the Ringland Academy, is a particularly relevant example [76]. Aiming to provide evidence for capping the traffic rings of the city, the role of civic movement was combined with the role of the knowledge network in order to feed public debate with evidence [34, 64]. CurieuzeNeuzen later evolved to the wider Flanders region of Belgium [29, 34, 64]. Another example is Mapping For Change [67]. The organisation has intervened in different locations worldwide, including periodic greater London campaigns or specific campaigns in African cities where citizen science collected ambient concentrations might be the only air quality records available [67]. Mapping for Change takes collective mapping and community based research approaches, and their campaigns show wider implications in aspects such as scientific literacy [77]. These two initiatives both use Palmes diffusion tubes for monitoring NO₂ concentration levels [29, 78].

Palmes’ sampler consists of an acrylic tube 7.1 cm long and 1.1 cm internal diameter and they can be hung at selected locations. Palmes tubes are thus simple, relatively cheap, easy to use, ideal to be deployed in large numbers over a wide area and thus providing good spatial coverage [23, 29]. Palmes tubes also comply with the data quality objectives (e.g. EU/WHO standards) and they are comparable to long-term limit values like annual average [64], a key and easy-to-understand value both for citizens and public bodies [29]. All these characteristics make Palmes tubes an attractive choice for citizen science initiatives [64, 67] such as the xAire project (Barcelona, Spain).

The xAire project was conceived as a pop-up citizen science initiative [79] within the City Station (a participative community-based initiative) as part of the After The End of The World exhibition at the Centre de Cultura Contemporània de Barcelona (an important

exhibition venue in Barcelona, 2017-2018). Under the general framework of art-science hybridized initiatives (e.g. [80]), several participatory research activities were taking place at the City Station, and the xAire project was the most ambitious one. A broad partnership was established to launch the xAire project with more than 1,650 participants, 10 professional research scientists (the authors of this article), about 36 teachers and 4 non-scientific organisations. To articulate this large participation and catalyze its impact in the city, the xAire project opted to make a general call to families through primary schools (with children between 7 and 12 years old) with a similar spirit to other experiences with students that link popular epidemiology and community based research [81]. The xAire project was built as an opportunity for families to meet and work together in an inclusive after-class activity that enabled families to directly intervene in a topic related to the health of their children.

As a partner of the xAire project, the Barcelona Education Consortia (public schools municipal network, Consorci d'Educació de Barcelona, CEB) engaged 18 primary public schools evenly distributed among the 10 districts of the city. Provided with a methodology guideline [82], after a training session and in a coordinated manner, the schools organised mixed groups of 4-5 people with parents and children and autonomously placed up to 800 Palmes passive diffusion tube NO₂ samplers following identical protocol and resulting in 725 valid data points (671 outdoor, 31 outdoor playground, and 23 indoor school, between February 16th 2018 and March 15th 2018, four weeks). In the case of Barcelona, large simultaneous sampling has only been conducted by professional scientists, and it has never reached more than 300 sampling points [21]. Each of the schools interpreted the data and provided a set of conclusions and demands during the Barcelona Science Congress, where young students were the presenters and the attendants, with the presence of the Barcelona Mayor. The schools also promoted the organisation of a non-initially planned event at the Town Hall where representatives for each school delivered results and demands to the Deputy Mayor of Ecology, Urbanism and Mobility, and the Commissioner of Ecology. Data was finally uploaded onto a digital mapping platform for public consultation [83]. Broad press coverage reported this unprecedented effort in the city of Barcelona throughout the project (e.g. [84, 85]).

Cost-effectiveness and the simplicity of the Palmes passive samplers [78] facilitates the inclusion of large numbers of citizens in a study that can bring several benefits to society while providing new scientific insights [62, 64]. However, compared to citizen science ini-

tiatives in other fields or topics, studies to demonstrate on a large scale (city level) the full potential of citizen science for air quality monitoring are still scarce and partial [64]. Some studies have focused on the methods and strategies being deployed [67, 76], while others on data quality and standards compliance [64]. Others show their societal impact through interviews [73] or highlight the need to take an inclusive approach in research design [74, 75]. The main goal of the current paper is thus to jointly present the results of the xAire project. We pay special attention to three key interdependent aspects that, from our perspective, can make citizen science practices an attractive approach to face air quality issues in our cities: (1) an unprecedented, reliable, and representative high-resolution air pollution level data; (2) an updated high-resolution air pollution exposure for Health Impact Assessment (HIA); and (3) an enhancement of community (and individual) knowledge and attitudes towards city-level collective responses to air quality issues. The main reason for this multifaceted approach in a single paper is precisely because it is at this broad level where potential of air quality citizen science initiatives can be fully perceived.

Results

Results are structured in three subsections. Firstly, urban NO₂ concentration data in a high-resolution level is carefully analyzed and data quality is discussed in terms of reliability and representativeness. Secondly, we show how the large number of spots enriches and updates current Land Use Regression (LUR, e.g. [86, 87]) models for both air pollution exposure and HIA in the case of asthma disease (for the 1-18 year old population). Thirdly, participants' knowledge and attitudes are reported to provide qualitative evidence on how the xAire project has increased public awareness and promoted bottom-up collective actions to improve air quality. To provide further context to the research outcomes, Figure 1 summarizes the different phases of the xAire research process, including co-definition and interaction with participants to select sampling sites, from the project inception to results interpretation that were publicly shared and motivated collective actions. The Methods sections provide detailed information on where the xAire project was created, on the preliminary test serving as a participatory prototyping effort, on the participatory process involving communities from 18 primary schools, and on the Palmes' passive samplers deployment following a common protocol, among other technical aspects.

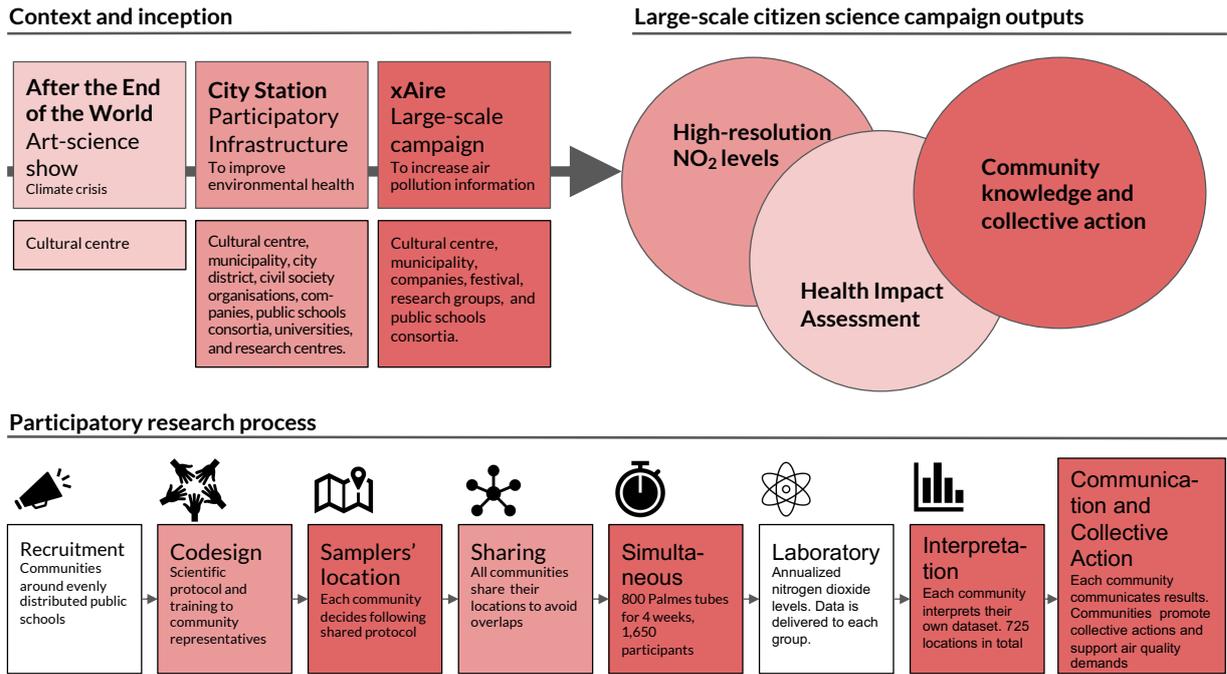


FIG. 1: A summary of the xAire project. Project inception and its context together with a description of each step in the participatory research process jointly with the interdependent outputs of its large-scale air quality citizen science campaign. Color intensity grades the intensity level of participation of the schools. Further details in Methods.

High-resolution NO₂ concentration levels

The xAire project distributed a total of 800 passive samplers to different school groups, and this joint effort finally resulted in a total of 725 NO₂ valid concentration level points (91% of the total samples, a slightly higher success ratio than a recent even larger air quality citizen science campaign in Belgium [64]). Figure 2 shows the map with all samplers' locations selected by participants.

Figure 3(a) verifies a high degree of precision and accuracy, and confirms that obtaining very good quality data in large-scale citizen science NO₂ campaigns is effectively possible. Furthermore, annual concentration adjustment factor to data can be applied [88]. De Craemer et al. [64] have recently shown the validity of this extrapolation procedure in a similar large-scale citizen science campaign. We will use the annual adjusted data in all the forthcoming analyses. See Methods, Data precision and accuracy section for further details.

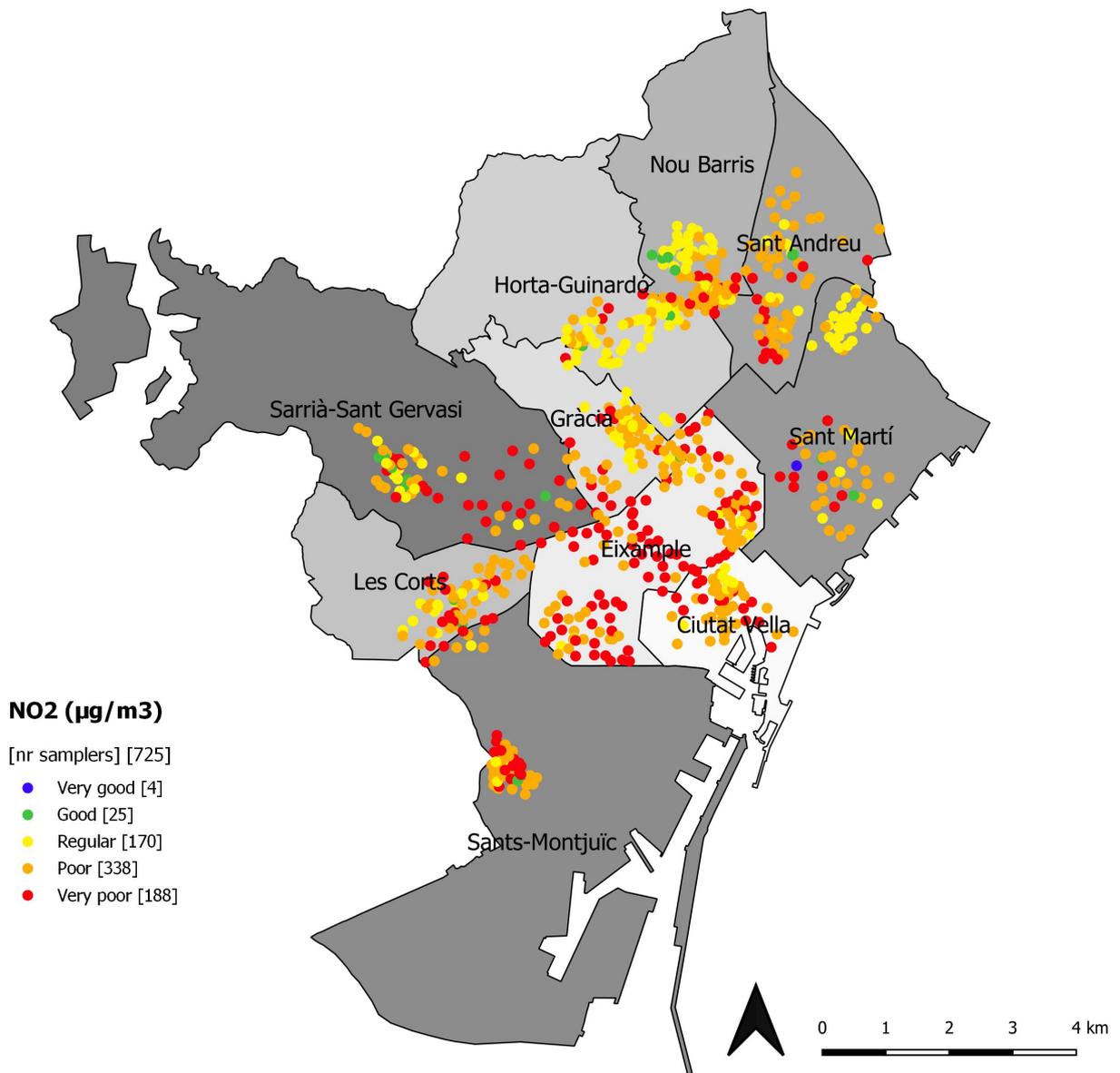


FIG. 2: Map with all sampler locations (n=725). It includes outdoor locations n=671, playgrounds n=31, inside school buildings mostly inside classrooms n=23 with colour code based on their annualized NO₂ concentration level. This is an English version of the map delivered to public authorities (see Methods Public presentations and Tables S1 and S2).

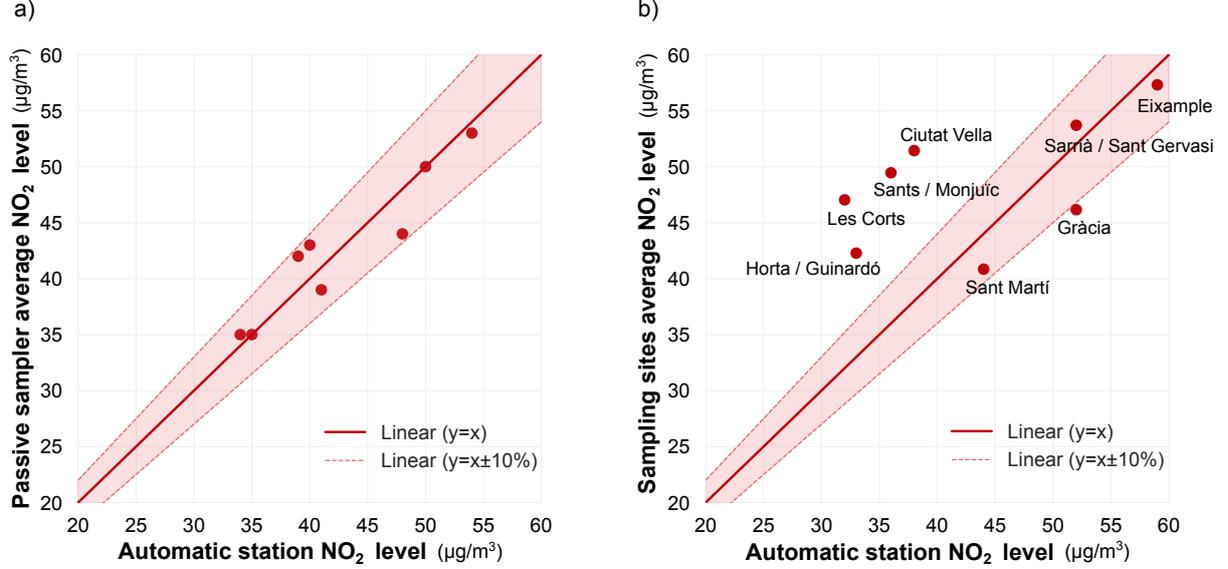


FIG. 3: **Samplers compared to automatic stations.** (a) Passive samplers (averaged triplicate Palmes’ diffusion tubes, co-located samplers at each station) linear regression (solid line) with respect to automatic monitoring stations. Dashed lines delimit 10% error tolerance, all samplers are within this uncertainty tolerance (dashed lines, see also Methods, Data precision and accuracy). (b) Annualized NO₂ outdoor (n=671) concentration levels comparison between the seven automatic monitoring stations and the average of xAire samplers when divided into the corresponding districts. Sarrià and Gràcia districts are assigned to the same automatic monitoring station [13]. There are two traffic automatic monitoring stations (Sarrià/Sant Gervasi or Gràcia and Eixample) and five background automatic monitoring stations (Horta Guinardó, Les Corts, Sants / Montjuïc, Ciutat Vella, Sant Martí).

Aligned to other studies made with and without citizen science strategies [16–19, 64] Figure 3(b) shows that passive samplers records describe relevant differences with respect automatic official monitoring stations (averaged annual monitoring reference [13]). In fact, the average overall passive samplers ($49 \pm 1 \mu\text{g}/\text{m}^3$) is higher than the Barcelona level averaged over the automatic official monitoring stations ($42 \pm 4 \mu\text{g}/\text{m}^3$, n=7 [13]). Indeed, 68% of the xAire outdoor samplers give higher values than the Barcelona level averaged over the seven automatic stations (see Table S1).

Figure 4 illustrates several statistical aspects related to the xAire passive samplers. Again

consistent with current literature [16–19, 64], Fig. 4(a) shows a large range of concentrations (mean= $49 \pm 1 \mu\text{g}/\text{m}^3$, median=45, Quartile 1=39, Quartile 3=55, Skewness=1.82, see Table S1). There is a considerable number of samplers (5%, $n=34$) that have concentration levels higher than $86 \mu\text{g}/\text{m}^3$. Figure 4(b) goes into more detail and discerns between traffic sites (mean= $52 \pm 1 \mu\text{g}/\text{m}^3$, $n=482$, 5% of the samplers show higher values than $89 \mu\text{g}/\text{m}^3$) and background sites (100 meters away from streets with motorized vehicles, mean= $41 \pm 1 \mu\text{g}/\text{m}^3$, $n=182$, 5% of the samplers show higher values than $56 \mu\text{g}/\text{m}^3$), thus confirming strong differences persist within this classification (see also Table S1). Averaged annual levels from traffic ($n=2$) and background ($n=5$) automatic official monitoring stations [13] are respectively 56 and $38 \mu\text{g}/\text{m}^3$.

Looking at the granularity for the 10 districts, boxplot in Fig. 4(c) and Tables S2 and S3 show that even within each district there exists a strong variability biased towards higher concentration levels. Background concentration levels are generally lower than traffic concentration levels. Figure 4(c) shows disparity among the 10 districts and this also becomes evident in Table S2 where in 3 districts 5% of the samplers show values at least higher than $89 \mu\text{g}/\text{m}^3$. In one of these 3 districts, 5% of the samplers have values below $28 \mu\text{g}/\text{m}^3$ (the lowest value over all 10 districts).

Schools were also interested in knowing the air quality in their playgrounds ($n=31$) and inside their schools ($n=23$, indoor, mostly inside classrooms). The xAire project left the freedom to each school to use some of the samplers for this purpose. NO_2 concentration levels are in both cases quite high. The playground outdoor mean level is very close to the EU/WHO threshold ($37 \pm 1 \mu\text{g}/\text{m}^3$, median=38, Quartile 1=34, Quartile 3=40, see Table S1). School indoor samplers broadly show, as expected, lower levels but they are broadly distributed ($31 \pm 3 \mu\text{g}/\text{m}^3$, median=28, Quartile 1=24, Quartile 3=36, Skewness=2.43, see Table S1). Both values are positively correlated (Pearson correlation $\rho = 0.34$, $n=15$). Linear regression $y = ax + b$ of indoor school levels with respect playground levels can also be performed albeit errors are high ($a = 0.24 \pm 0.17$ and $b = 28 \pm 5 \mu\text{g}/\text{m}^3$).

Regarding the question of whether samplers' location can be considered to be representative, participant's selection may result in underexplored areas and general conclusions from the data collected may be thus questioned. Spatial representativeness is indeed a key question raised in environmental monitoring or collective mapping citizen science projects [36, 39, 45–48, 51, 53, 89–91]. In the context of citizen science and air quality monitoring,

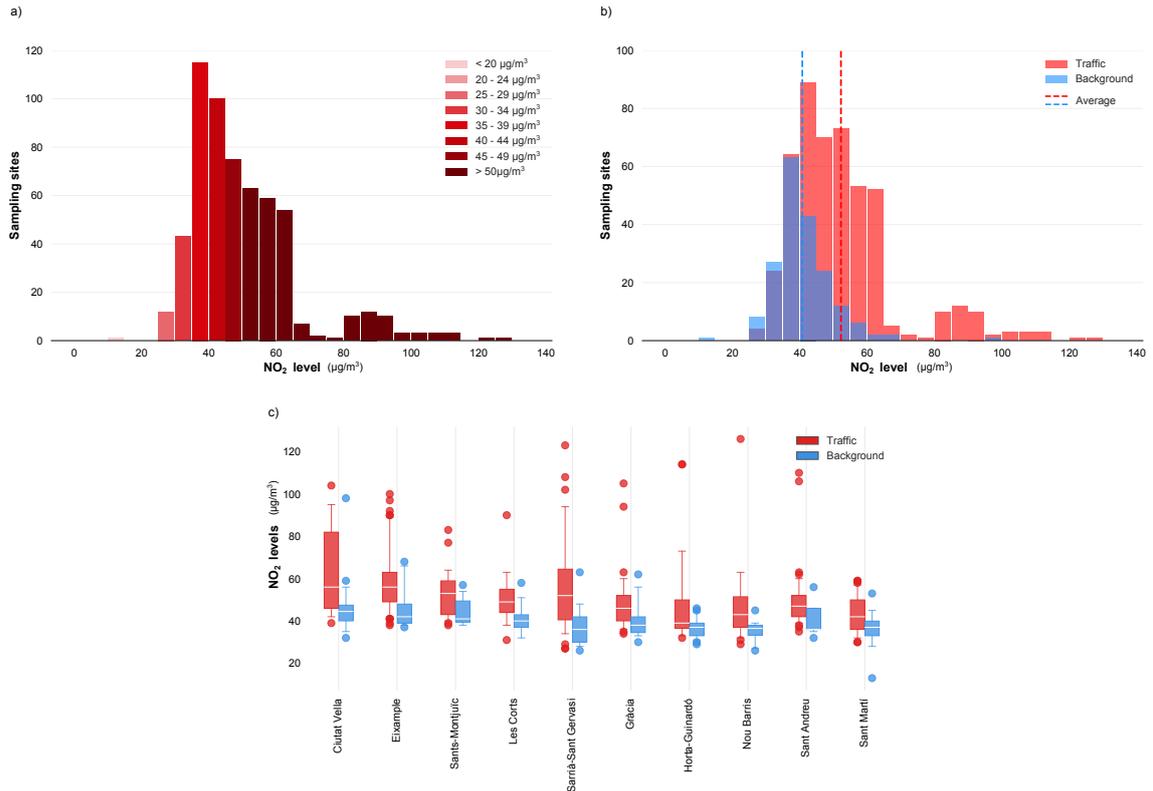


FIG. 4: **Statistical aspects of passive samplers.** (a) Distribution of sampling sites with respect to their NO₂ outdoor concentration levels. (b) Disaggregated traffic (red) and background (blue) distributions of sampling sites as a function of their NO₂ concentration levels. Vertical dashed lines correspond to mean values of traffic (red) and background (blue) samplers. (c) Disaggregated traffic (red) and background (blue) NO₂ concentration levels for every district including median (white line), interquartile (between 25% and 75%, boxes) and 95% confidence intervals (bars).

there is still no literature to evaluate this issue. Since xAire aimed to evaluate representativity in terms of air pollution exposure and HIA for Barcelona inhabitants, we evaluated the outdoor samplers' spatial distribution and compare it with the population spatial distribution all over Barcelona at the smallest scale available [92] (census tract scale, few blocks).

Figure 5(a) shows that both distributions are very similar and the two-sided Kolmogorov-Smirnov test allows us to state that participant's selection is representative enough to undergo an air pollution exposure analysis (KS test: 0.05, p-value: 0.32, see Methods Kolmogorov-Smirnov test and Pearson correlation). The average population per census tract

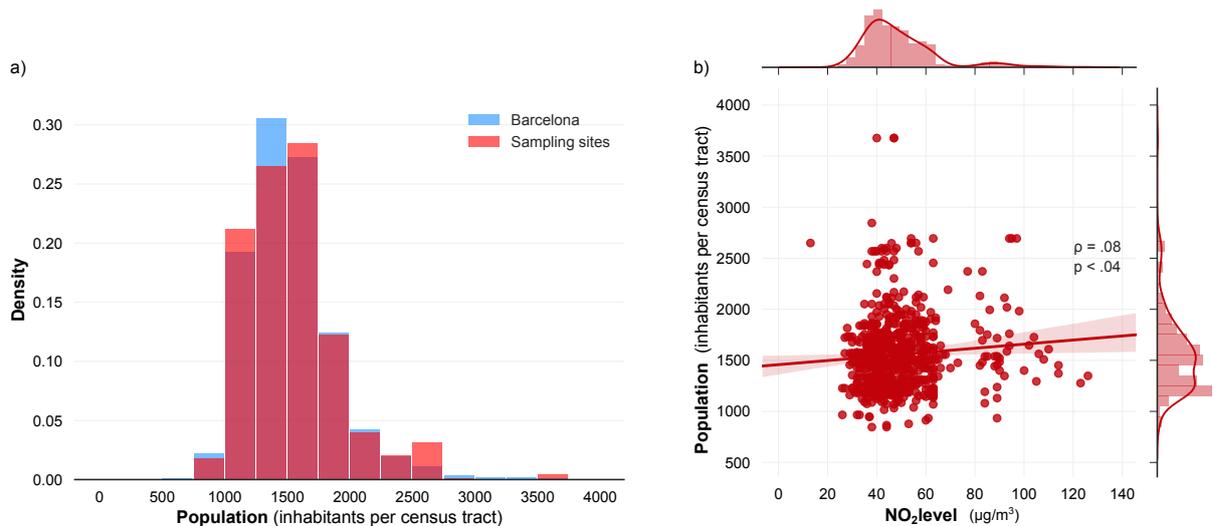


FIG. 5: **Distribution of passive samplers sites.** (a) Distributions of population (red, $n=1,068$) and distribution of samplers (blue, $n=671$), per unit of census tract. (b) Scatter plot between NO₂ concentration levels and population in each census tract (Pearson's $r=0.08$, p -value= 0.035). See Table S4 for detailed statistical traits.

in Barcelona ($n=1,068$) is $1,525 \pm 11$ ($SD=358$) while the equivalent one by taking the sampler's location is $1,556 \pm 15$ ($SD=383$, $n=671$). Table S4 provides further statistical details. Similarly, and at least as a test-bed, we can perform the analysis with the income spatial distribution [93] showing a much weaker similarity which leads us to conclude that our sample spatial distribution is not representative of Barcelona income spatial distribution (KS test: 0.11, p -value: 0.0001, Fig. S1(a) and Table S4). If the research aimed to incorporate this economic dimension [62], it would be then necessary to change participatory protocols or to engage alternative or additional communities, in our case evenly distributed communities around public schools across Barcelona and somewhat under-representing wealthier neighborhoods.

Finally, the current analysis also allows the study of the correlation of NO₂ concentration levels with population (see Fig. 5(b)) and with income (see Fig. S1(b)). See also Methods Kolmogorov-Smirnov test and Pearson correlation. Correlations are in both cases small, but income is observed to be more relevant in relation to air quality exposure and, maybe in contrast to other cities, it is positively correlated with income [62].

LUR model and asthma exposure

The best Land Use Regression (LUR) model [17, 86, 87, 94] found includes as covariates: the total traffic flow (total vehicles per day passing through) within 25m and 100m circular buffer, building density (total terrain surface covered by built area) within 100m circular buffer, site type (the sampling location characterization in terms of traffic flows, e.g. traffic or background), the interaction of traffic flow within 25m with district sampler location (x and y coordinates, $k = 10$ in Barcelona) and a Generative Additional Model spatial component. The air pollution concentration levels:

$$\text{NO}_2 \sim \text{trafflow}_{25} + \text{trafflow}_{100} + \text{build}_{100} + \text{type} + \text{trafflow}_{25} \times \text{dist} + s(x, y, k = 10)$$

The best model performance using the xAire data was found for a scenario with a total of 370 sampling sites after excluding samplers placed within 25m from a street intersection or a bus stop and in addition to removing all influential observations based on standard Cook's distance. See Methods, Land Use Regression model for further details about the procedure. It represents a larger number of samplers than in any other previous simultaneous study in Barcelona [21]. Adjusted R² (0.60) and leave-one-out cross-validation R² (0.55) provided a moderate model performance, a bit lower than most of the models published, which are around 0.70 and 0.80 [86, 87]. Participants' sampling selection could explain these small differences since site selection in LUR models is systematically applied for ensuring the best model performance.

The number of sites used in the xAire project for LUR modelling are well above the 80 measurement points being used in previous NO₂ air pollution exposure [95] and the minimum of sites required (n=120) to obtain a stable and reliable model performance [96, 97]. The latter studies have shown that models with a higher number of sampling sites produce a better model performance and less chance of including noisy predictor variables into the model [96, 97].

The xAire data also allowed for an updated and high-resolution picture of health impacts related to NO₂ in Barcelona. A quantitative HIA framework was used to estimate the childhood asthma cases attributable to NO₂ concentrations in a census tract level (see Figure 6), as described in Table I, Methods, Health Impact Assessment, Figure S2 and References [8, 10]. Using the WHO guidelines (annual concentration of 40 $\mu\text{g}/\text{m}^3$ of NO₂ [14]) as counterfactual exposure, the HIA analysis estimated that 225 cases of asthma in children

Scenarios 1 and 2	% Asthma cases LCI UCI			
Comparing with WHO guidelines (40 $\mu\text{g}/\text{m}^3$)	9	225	96	302
Comparing with minimum reported levels (1.5 $\mu\text{g}/\text{m}^3$)	42	1,084	515	1,364

TABLE I: **Results estimating the percentage and number of annual asthma cases in children (1-18 years old) attributable to NO_2 .** We use xAire data from Barcelona in two different scenarios. LCI: Lower confidence interval of asthma cases; UCI: Upper confidence interval of asthma cases.

(1-18 years old), around 9% of all asthma cases in Barcelona, could be attributed to NO_2 concentrations. In addition, using a counterfactual exposure of 1.5 $\mu\text{g}/\text{m}^3$, the HIA analysis estimated 1,084 cases of asthma in children could be attributed to NO_2 concentrations, 42% of all asthma cases in Barcelona. These figures are consistent with previous studies estimating asthma related to air pollution in children in Barcelona, which suggested that 48% of all asthma cases in children could be attributed to NO_2 (1.5 $\mu\text{g}/\text{m}^3$ threshold and for year 2009) [10]. Furthermore, it suggests that the current WHO guidelines are not strict enough to prevent many of the annual cases of childhood asthma in Barcelona (n=859).

Knowledge and collective action

After approximately four weeks, the xAire project returned the data to each school group (through teachers and family representatives). All school groups autonomously and independently discussed the NO_2 concentration levels in their districts according to the sites selected (with 40 samplers each, inside and around the school, see Methods, Participatory process). The results were mostly discussed in terms of the WHO and EC limit values [2, 14] with special attention to those sites far beyond these limits. Table 2 lists the school names jointly with their codename and the student’s age and grade. Methods, Public presentations provide the details on the context where participants presented the research results.

The discussions demonstrated a clear understanding of the monitoring data and on the process of scientific inquiry: 7-8 year old children were able to perfectly explain the scientific protocol to a regional TV (JM school [84]) or during the Science Congress organised by the Barcelona Education Consortia (e.g. ES school with 11-12 year old children [98], and JM school with 6-7 years old children [99]). During the official meeting with representatives of

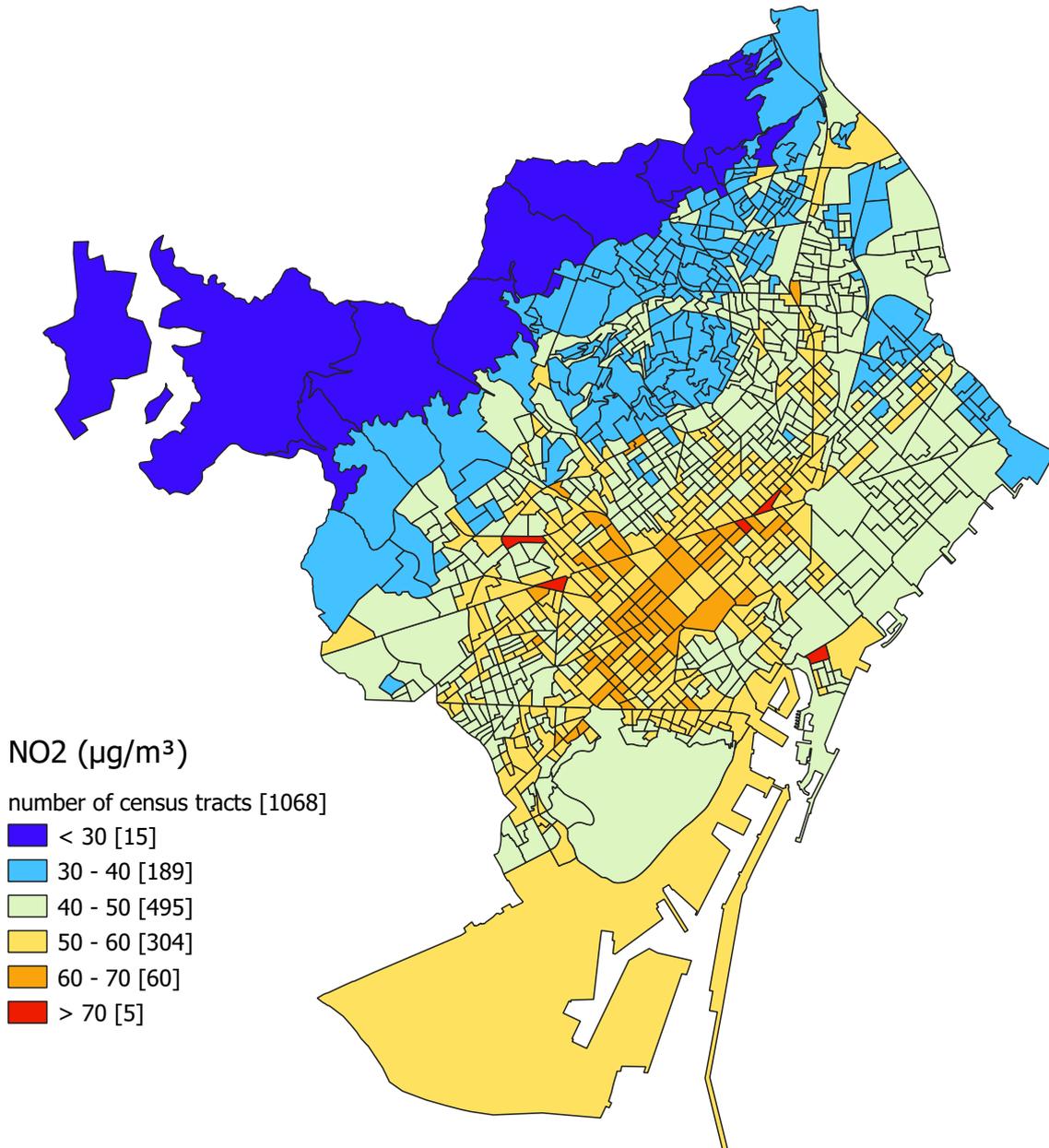


FIG. 6: **Barcelona map of NO₂ concentrations at census tract level (n=1,068).** The LUR model is implemented to the optimized xAire data set (n=370). Color grid varies depending on the NO₂ concentration levels.

the City Council, students pointed to the correlation between air quality and traffic density or between air quality and the lack of green spaces [100]: "We had to locate traffic and background spots: we rapidly noticed that we had not many background locations. This

means that in our neighborhood (Sant Andreu) there are not enough green areas” or “We located two spots in Avinguda Meridiana since we believed that, there, the nitrogen dioxide levels would be higher than in other places, and we were right” (CF school); “A very clear correlation is observed between air quality and traffic density” or “What contributes most to the poor air quality in our neighborhood is the traffic ring of the city” (at DM school, they retrieved additional data on traffic to support these two statements, see also [101]); “Our school is located in a touristic area, where there is a lot of traffic, both cars, buses and coaches. This explains that in some of the locations we have obtained values greater than $70 \mu\text{g}/\text{m}^3$ ” (SF school); “Tubes with poor or very poor air quality are the ones on the busiest streets and with a large number of vehicles” (TB school), “We observe that locations close to Passeig de la Zona Franca and Ildefons Cerdà square show high levels of nitrogen dioxide because there is a high traffic density” (SE school) [102].

Since the diffusion tubes were often located in the home-to-school path [98, 103], the results were relevant to students, and they were able to make a diagnosis on their own with no professional scientific supervision and noticed that “it was not easy to find a non-polluted pedestrian path to go to school” (ES school [98]). EH school studied the difference in NO_2 levels: “Larger streets showed higher levels due to the high traffic density” [104]. Observations were also made regarding green areas [100]: “Air quality was qualified as ‘very good’ only in a little park surrounded by buildings.” (SM school); “In the fewest green areas we have in the neighborhood, the air quality is qualified as ‘poor’ or ‘moderate’” (SF school). The results also generated surprise [100]: “This data tell us we are exposed to a ‘moderate’ level of pollution, which, given where our school is located, we expected a better rate” (AG school); “Most of us think that it is a neighborhood where there are many parks and with the Superilla the air should be cleaner.” (SM school, Superilla/superblock is an urban intervention that reduces motorized vehicles).

The students indeed reported that the data collection process enhanced their connection to place and awareness about air pollution exposure in their school and district while considering possible effects in health and well-being [103, 104]. Results explicitly generated concern when related to health [100]: “Only one tube showed a good air quality” (PC school) [105]; “We have an average of $50 \mu\text{g}$ per cubic meter and this makes Ciutat Vella district the second district most polluted in Barcelona. Very sad news for us!” (CE school); “Our school is surrounded by three highly polluted streets which we also have found to be

Primary School	Code	District	Age (years old)	Grade
1 Els Horts	EH	Sant Martí	10-12	5th, 6th
2 Sant Martí	SM	Sant Martí	10-11	5th
3 El Sagrer	ES	Sant Andreu	11-12	6th
4 Can Fabra	CF	Sant Andreu	11-12	6th
5 Calderón de la Barca	CA	Nou Barris	7-8	2nd
6 Timbaler del Bruc	TB	Nou Barris	9-10	4th
7 Pau-Casals	PC	Gràcia	8-9	3rd
8 Sagrada Família	SF	Gràcia	9-10	4th
9 Joan Miró	JM	L'Eixample	7-8	2nd
10 Fort Pienc	FP	L'Eixample	11-12	6th
11 Dolors Monserdà Santa Pau	DM	Sarrià-Sant Gervasi	11-12	6th
12 Seat	SE	Sants-Montjuïc	9-10	4th
13 Àngels Garriga	AG	Horta-Guinardó	10-11	5th
14 Coves d'en Cimany	CC	Horta-Guinardó	10-11	5th
15 Àngel Baixeras	AB	Ciutat Vella	11-12	6th
16 Cervantes	CE	Ciutat Vella	11-12	6th
17 Les Corts	LC	Les Corts	11-12	6th
18 Lavínia	LA	Les Corts	11-12	6th

TABLE II: **List of public primary schools involved in the xAire project.** The columns include information related to the code name used, the district, the age range (in y.o.), the grade of the students.

those with more dense traffic“ (ES school, the school measured the traffic flow on their own [98]); “The air quality in front of the school is “very poor” (JM school); “In our playground the air quality is qualified as “moderate” and “poor”, that is the reason why we are very worried” (SF school); “We find it very worrying that the air we breathe when we are doing Physical Education or when we are playing at the playground. The air is unhealthy where we do outdoor activities at our school and where we do extracurricular activities. [...] We are especially concerned about our younger teammates because they are breathing polluted air when they are at the playground.” (LC school). The students correlated the results

with health impacts [100]: "Not having good air quality implies: more respiratory diseases, interferences in the cognitive development of school-aged children" (AG school). They also demanded public authorities to take some action [100]: "The air quality we breathe in our district is poor. And we believe that it is very necessary to look for urgent solutions to this problem." (SF school); "The average level in our district is 45 μg per cubic meter, which implies that the air quality is poor. This is worrying us and we hope you can take some action" (CF school); "We ask you as policymakers to consider the action plans we propose with the aim to improve our health and the health of our city" (JM school).

The measures proposed by the young students during the event with public authorities ranged from the promotion of use and (economic) accessibility of public transport in the neighborhood (DM, JM, AG, and SE schools [100], and also TB school [106]), the promotion of pedestrian routes (JM, AG, SE, and AB schools [100]), a substantial increase of green areas and pedestrian streets (ES, CF, JM, LC, and SE schools [98, 100, 107]), installing parking lots to persuade commuters to not enter to Barcelona with private cars (DM school [100]), covering the ring road (DM school [100] and [101]), limiting car circulation or shifting from combustion to electric vehicles (DM, JM, AG, AB and FP schools [100, 108]), or promoting the use of bikes and electric scooters with new lanes (DM, SE, AG schools [100] and TB school [106]).

Furthermore, families' engagement - who received training, collaborated in the planning and implementation of the samplers location - was excellent. Large numbers of families showed willingness to come to an evening training session, which turned into a general assembly to agree on a shared protocol (see Methods, Participatory process). They also collaborated in the decision-making process of the places where samplers were installed, in the deployment and removal of the samplers, and in several events to promote change based on data collected. A mother from SF school said "I've always been very involved in school. I did not hesitate to be part of the project and also learn about air quality sensors" [85]. The supportive engagement of students' parents and relatives points to how environmental awareness and advocacy could be diffused through peers and social networks [115]. SF school evaluated the activity during their presentation in front of the public authorities, describing xAire as [100]: "a fun activity. [...] We learned a lot of different things and it helped us get to know the neighborhood better". Beyond scientific skills, the teachers agreed that the xAire project helped the students see the social value of the knowledge produced within

the class group. A teacher from JM school explained that “when kids see that behind an activity there is a reason and an intention, they feel fulfilled” [85] and another teacher from SF school stated: “They are at an age that all excites them, they are very receptive, they cheer up right away. I am convinced that they will never forget this experience” [85]. The teacher from SF also stated that “it has [also] been a stimulus for her. If the teacher is motivated the students too.” [85]. She also admitted that although “[It] was an intense work at the team level, they generated digital skills and, above all, they are now very aware after learning about how air quality affects their health and their learning performance. Such intense experiences, also have an effect inside families” [85].

Most of the schools took further action beyond data collection and discussion within the xAire planned activities and disseminated their results in a number of local events and in front of a variety of audiences (see Methods, Public presentations). The SF group came together with their families (more than 40 people) and teachers to actively participate in the Barcelona Science Festival and autonomously presented the results of the research to the public. Another school group of about 20 students (SM) arranged the presentation of their results in front of an adult audience at the Barcelona Mobile Week, which triggered a vivid debate in the audience that continued on Twitter afterwards about the benefits and pitfalls of the Superilla urban intervention in the district. ES and TB schools started a local campaign with families and neighbors [98, 106]. ES school submitted a formal petition to remove traffic in a central and congested street in the district (Av. Meridiana) and surrounding area, and finally presented the results in front of the Mayor at the opening of the Science Congress and directly asked her to immediately start the major works already planned to reduce traffic and increase the amount of green space [98]. CF school, based on their concern on air quality, decided to introduce plants inside classrooms through a new research project [107], TB school chose new or modified the plant species in their garden by considering their capacity to absorb pollution [106], and SF and TB schools started to construct vertical gardens in their school playground [103, 106].

Discussion

This paper describes the experience of a large-scale and unprecedented citizen science monitoring campaign in Barcelona (Spain) with NO₂ passive Palmes diffusion tubes [2, 78].

Eighteen primary schools evenly distributed in the 10 city districts and 1,650 participants (7-12 year old children, their families and teachers) deployed 725 samplers across Barcelona (671 outdoor samplers, 31 in playground and 23 inside school buildings), selecting their locations and autonomously interpreting their NO₂ concentration levels. We have reported the multifaceted outcomes of the xAire project to support the broad statement that citizen science can contribute to air quality monitoring in its interplay between advances in environmental exposure assessment and developments in policy [2, 35, 42, 62, 64, 109]. We further assess the health impacts that air pollution levels have in the city. The xAire project is an example of how a broad partnership is able to enhance community (and individual) knowledge and attitudes towards city-level collective response to air pollution exposure [73–75].

There is already a large number of opportunities for high-resolution measurements of air pollutants in cities [54–61]. Due to the increasing evidence of adverse health effects, the related technological and scientific efforts need to be accompanied by actionable insights that harness policies, recommendations and collective actions both at a city level and at a high-resolution (neighborhood, census tract) level [62]. However, public support for policies might be jeopardized due to the public perception of lack of information or the unsatisfied desire of citizens to express their own views on air quality issues [28]. Therefore, it seems necessary that rigorous and robust scientific methodologies offer citizens an active role in the scientific research process. Citizen science practices, broadly defined as the participation of the public in research [30, 31], can offer this space.

In xAire, communities (class groups jointly with families and teachers) have successfully delivered reliable data following a shared protocol that was jointly agreed, and co-designed in a preliminary testing phase which was built upon previous experiences [67]. The distribution of NO₂ concentration levels reported was ample and revealed high to very high levels (5% of the samplers, n=34, show levels higher than 86 $\mu\text{g}/\text{m}^3$), thus confirming that air quality is a serious issue throughout Barcelona, also at a high-resolution level. Extending participation by selecting the sites and by informing and autonomously interpreting the results obtained might indeed explain the high quality of the data (high success ratio in sample deployment and with satisfactory meta-data) which circumvents the risk of low quality data due to the fact that non-experts may report less information than experts [110].

Participatory processes also have the risk of a lack of representativeness in the distribution of samplers at a city level. Representativeness is a key discussion in biodiversity monitoring

with citizen science practices. Some articles have already highlighted the need to statistically handle biases [36] of spatial data due to particular amateur preferences for species and habitats [89, 90]. In some experiences, citizen science monitoring is then reduced to a complementary support to the ongoing conservation management efforts [91]. Unfortunately, there is still no systematic agreement about how to deal with these issues in air quality citizen science campaigns. xAire considered representativeness in terms of population spatial distribution as the project was oriented to health impact evaluation. Spatial population distribution of xAire sampling in a census tract level has been shown to be consistent with city spatial population distribution but it has shown inconsistencies with inhabitants' income spatial distribution. Participatory design process (recruitment and research protocol) thus necessarily needs to be reconsidered if a different research question is posed.

The air quality map generated by xAire represents an invaluable tool to estimate current exposures to NO₂ in Barcelona: it used an increased number of measurement sites compared to previous models with samplers distributed by professional scientists, and an updated (and therefore more realistic) set of concentration levels. To conduct the HIA for asthma cases, we developed the LUR model [17, 86, 87, 94] with 371 sites out of the 671 samplers deployed by citizens. This number can be understood as a minimal necessary number to obtain a complete picture of Barcelona, and greatly extends previous measurements [21, 95–97]. The study shows that new methods to efficiently integrate citizen science contributions in these models are urgently needed, in the same way as new methods have been recently demanded in the context of air quality compliance and policy support [64]. Furthermore, at a practical level, the estimate of childhood asthma cases attributable to NO₂ concentrations (in terms of percentage) in a census tract level provided by our citizen science approach is found to be statistically consistent with previous contributions in the literature [9]. It also shows the large impact that air pollution still has in the city, with more than a 1,000 new cases of childhood asthma in the city each year. The result also encourages the implementation of large-scale air quality citizen science campaigns in those cities that lack automatic monitoring systems [67, 111]. All these different outcomes reinforce the idea that citizen science practices can effectively contribute to environmental exposure assessments and policy.

Perceptions are an important component of behavior change and shape public response to environmental management [112]. Governments are grappling with how to empower

citizens to be involved in various aspects of environmental management [29, 113, 114]. While acknowledging the potential of community and individual level interventions for reducing exposure to air pollution and improving public health, citizen participation in data collection and environmental monitoring can play a major role in increasing environmental awareness by improving peoples' perceptions of exposure and risk for individual acceptance and action [115–117]. Overall, participation in crowd-sourced collection of air pollution exposure can therefore contribute to promote knowledge and understanding of the practice of science [118] and relevance of scientific outcomes, but also improve environmental awareness and advocacy [115–117].

Finally, large-scale air quality citizen science campaigns should not be simply seen as a public awareness (or a science dissemination) activity and a hands-on education programme [119]. Lower intensity level of participation is extremely valuable and might be seen as sufficient by professional scientists to engage citizens, but it does not guarantee per se a rigorous collection of high-resolution and representative air quality data nor an improvement in current air quality exposure maps, LUR models or health impacts. With a more intense participatory component, such as research co-design [120], participants can anticipate benefits which in turn are organically incorporated in the project design. This citizen science approach adds sophistication to the scientific research process as it requires multidisciplinary professional scientists and the involvement of non-academic organisations, such as school networks (see also the recent Clean@Schools [121] experience) and is not limited to public agencies. Public presentations showed that the xAire project has substantially increased the students' (aged between 7-12 years old) and their families' knowledge and understanding of air quality measurements. Participants were also able to evaluate the relation of motor vehicles and internal combustion engine emission with NO_2 . Through placed-based learning [116, 119] and the use of scientific standards and methods as a means of verification [122], citizen science has proven to contribute to improved risk identification, problem-solving [123], environmental stewardship [117], advocacy [115] and conservation action [116]. Active citizen support and new forms of communication among experts and citizens and the involvement of all major stakeholders are crucial to find and successfully implement health promoting policy measures.

Methods

Context

The xAire project was conceived within the City Station participative community-based project as part of the After The End of The World exhibition at the Centre de Cultura Contemporània de Barcelona (October 2017 to May 2018), and built with the artist and engineer Natalie Jeremijenko. The exhibition was devoted to climate change with a highly experiential mode. As part of the exhibition, City Station was a public space and infrastructure to enable several actions for improving environmental health in a participatory manner (November 2017 to April 2018). City Station was placed in a community space (Passatge Trullàs, Barcelona) in collaboration with the Barcelona City Council and the Taula Eix Pere Quart (civil society organisation). City Station was conceived as a citizen platform that, with the support of a broad list of scientific research groups and united the effort of neighbors, collectives, cooperatives of the Poblenou neighborhood.

Preliminary test

During discussions with groups of citizens and several scientific research groups at City Station (see Methods, Context), the decision was taken to conduct air quality measurements due to the lack of air quality information for the general public in specific points in the city, but also due to the lack of extensive high-resolution scientific studies in Barcelona. In order to gain practical experience in participatory air quality monitoring, and inspired by the experience of Mapping for Change in London [67], as part of a COST Action programme grant, some of the authors and a group of about 40 neighbors jointly designed first protocol while installing 40 passive diffusion tubes samplers in the Poblenou neighborhood. Special attention was given to locate the tubes inside and outside of a Superilla area (superblocks) where, not without public controversy, the municipality had recently pacified motorized vehicles (air quality samplers' installation: November 12th 2017; removal: December 15th 2017). Based on the pilot, revisions were made to the protocol that was then presented to the schools in the participatory process. For example, in the pilot phase, several tubes were placed at bus stops, but all of these tubes were removed, so this sampling location was excluded in the revised protocol.

Participatory process

Through the Barcelona Education Consortia (Consorci d'Educació de Barcelona, CEB) we firstly explored the potential interest of schools and families to participate in the xAire project. An initial meeting was organised on November 30th, 2017 with Primary school teachers. The feedback was very positive and enthusiastic. Due to logistics and budgetary limitations, the CEB chose between one and two schools per district based on the strength of their commitment and their diversity (18 in total). Primary schools were engaged through their teachers and decided which specific classes and groups from their schools would participate and then invited families to join. The list of 18 schools with its code name, district, grade and age range is reported in Table II. A massive afternoon training session for teachers and families was then organised and the whole scientific protocol was discussed with more than 200 educators and family representatives from all 18 schools engaged (January 18th, 2018). The training session used an assembly format and included key aspects of Palmes diffusion tubes samplers (see Methods, Measurement technique). After the session, the protocol was revised again and sent via email to the focal points established at each school. The protocol guide included the objectives of the initiative, a description of the key players, a calendar with milestones, and a detailed, step-by-step description on how and where to place the diffusion tubes [100]. After this session, each class group was asked to plot the 40 tube samplers on a map during class hours, at home (with families), and eventually during a walk in their respective neighborhoods. They chose their preferred locations through discussions with teachers and families in accordance with the following criteria: 1) each school had to include one location at the main entrance of the school, one at the playground and one indoors 2) the rest of the samplers were to be deployed outdoors aiming to achieve background (at least 10% of the samplers 300 meters away from motorized roads) and traffic-orientated locations, avoiding specific spots such as bus stations and intersections, and placing tubes at least 100 meters distance apart from each other. One week before starting the collective sampler placement, and to avoid overlaps or anticipate problems, each school delivered a map to the xAire coordination team indicating where their tubes would be located. An overlap in the locations in two schools and a too dense tube's distribution in one school were detected. These resulted in a revision of half a dozen sampler locations. School representatives came to pick their 40 samplers on February 15th 2018, one day before deployment.

This meeting served to finalize logistics details and resolve remaining doubts or questions. The samplers were installed simultaneously on Friday, February 16th, 2018, around 5pm, and they were removed 4 weeks later (the optimal time window to maximize Palmes diffusion tubes precision [64]). Groups spent up to 2 hours to complete their deployment routes.

As described in the protocol [100], each group brought a small ladder to place the samplers at approximately 2.20 meters high with their clip. Each tube was identified with a four digit numeric label. The participants then completed a paper based table with the following information: the address and the GPS coordinates (using their own mobile phones) together with the reference code of each tube. Each sampler was also classified depending on its location: indoor (inside the school), playground (outdoor), outdoor urban traffic and outdoor urban background. The same operation was repeated during sampler removal (March 15th, 2018). Installation and removal forms were completed using a double check procedure: using mobile phones, participants took a picture of each tube (clearly identified) in its location. Each school uploaded all documentation into an online form jointly with scanned versions of the paper tables to double check any inconsistencies.

Public presentations

Campaigns were extensively covered by local media (newspapers, agencies, and local and regional TV). Students and their teachers presented with no mediation the results in front of journalists (e.g. JM and PC schools) with no mediation. The second public presentation was during the annual Science Congress (May 22-24th, 2018) organized by the CEB for public primary schools from Barcelona to meet and share their research on a numerous set of topics related to sustainability. Their contributions were recorded and are publicly accessible on the congress website [124] with YouTube streaming. Eleven schools involved in the xAire project further requested an official meeting with local administration representatives to share their results. The leaders of the xAire project facilitated the organisation of a joint visit to the city council (Saló de Cent, April 26th 2018 as reported in the Barcelona City Council [125]). Approximately 200 students (between 7 and 12 years old), families and teachers were received by the Deputy Mayor in Ecology, Urbanism and Mobility, and the Commissioner of Ecology. During a 1h30m session, 22 student representatives (two per each school) presented their own investigations, formally delivered the results to the city and

demanded specific actions from local authorities. For this event, each school drafted a final report that was given to the Deputy Mayor and the Commissioner [100]. In addition, the SF school group came together with their families (more than 40 people) and teachers to actively participate in the Barcelona Science Festival (June 9th 2018). Another school group of about 20 students (SM) arranged the presentation of their results in front of an adult audience at the Mobile Week (February 20th 2018, within the Barcelona Mobile World Congress programme).

Measurement technique

Ambient concentrations of NO₂ were measured using Palmes-type NO₂ diffusion tubes [78]. These passive air quality samplers absorb the pollutant to be monitored directly from the surrounding air and need no power supply. They consist of an acrylic tube 7.1 cm long and 1.1 cm internal diameter, two stainless steel grids and two caps. A chemical reagent is used to absorb the pollutant to be measured directly from the air. The absorbent used is 20% triethanolamine (TEA) deionized water. The stainless steel grids at the closed end of the tube are coated with this absorbent. The transport of NO₂ through the tube is done by molecular diffusion process [126], since during sampling one end is open and the other closed. After sampling, the exposed tubes are analysed using a Spectrophotometric technique. The concentrations of Nitrite ions, and hence NO₂, chemically adsorbed are quantitatively determined by UV/Visible Spectrophotometry with reference to a calibration curve derived from the analysis of standard nitrite solutions (UKAS Accredited Methods). The passive samplers used have two limitations. Firstly, they are categorised as an “indicative” monitoring technique, which refers to a technique with relatively high uncertainty ($\pm 25\%$ according to EU CAFÉ Directive [127]). Whilst ideal for screening surveys, or for identifying locations where NO₂ concentrations are highest, they do not provide the same level of accuracy as automatic reference monitoring techniques. Secondly, as the exposure period is typically several weeks, the results cannot be compared with air quality standards and levels based on shorter averaging periods such as hourly [126]. However, they are fully comparable to long term limit values like annual average, as presented in this paper.

Data precision and accuracy

Diffusion tube precision can be described as the ability of a measurement to be consistently reproduced, i.e., how similar the results of triplicate tubes are to each other. This is calculated with the coefficient of variation (CV) of triplicate tubes results. Passive samplers may under or over estimate NO₂ concentrations, resulting in a relatively moderate uncertainty. For this reason, during the measurement campaign, diffusion tubes were exposed in triplicate at 8 reference automatic official monitoring stations in the study area (one was very close but outside the Barcelona municipality). The monitoring stations included different types of stations classification according to EU Directive [20]: urban traffic (3) and urban background (5). The co-location with automatic monitors allowed calculating the precision and accuracy (bias).

A “good” precision applies where the average CV of all triplicate results is less than 10% [88]. In this study, the average CV was 3.9%, with a range between 0.9 and 7.8%, indicating a good precision. The accuracy of diffusion tubes (bias) represents the overall tendency of the diffusion tubes to depart from the true value, i.e., to under or over-read relative to the reference method (the chemiluminescence analyser). In this case the average bias adjustment factor was 1.07, which means that tubes underestimated 7% of NO₂ concentrations, so the results were adjusted using this factor. This bias implies an uncertainty within $\pm 10\%$ which represents a good accuracy level. As a further control measure, travel blanks were used across the study to detect any contamination during the shipping. The results of the blanks were below the detection limit. As the measurement campaign was 4 weeks (February-March 2018), the results could be influenced by the environmental conditions of this period and may not be representative of the annual mean. Thus, the results were adjusted to estimate an annual mean concentration using the 2017 NO₂ annual mean at each reference station. The average ratio between annual means and period means was 0.96, which was used as an adjustment factor. Key meta-information was also collected for each site by each school during the deployment and collection: site name, site type, latitude and longitude. The exact location of the sites was obtained by different means: GPS readings on site using phones or tablets or using desktop tools like Google Maps. The team reviewed all site locations on a semi-manual process to ensure all locations were reported accurately, which was the case for more than 90% of the samplers.

Kolmogorov-Smirnov test and Pearson correlation

The representativity of the xAire samples regarding income and population in Barcelona were analyzed by means of a two-sided Kolmogorov-Smirnov test in order to know if both samples were drawn from the same continuous distribution. We reject the null hypothesis if p-value is lower than 0.05, meaning that the independent samples are not drawn from the same continuous distribution. Linear correlation between NO₂ levels and, income and population distribution respectively, was tested by means of Pearson's correlation coefficient. Results are shown in Figs. 4 and S1 while additional features are provided in Table S4.

Land Use Regression model

The Land Use Regression model (LUR) approach was used to create an air quality map and determine the exposure assessment to NO₂ using the xAire data. LUR is a statistics-based method often used in epidemiologic studies to predict the air pollution exposures. This is based on true air pollution data measured on a certain number of sites and a set of predictor variables available through Geographic Information Systems (GIS) characterizing the surrounding environment [17, 94]. 671 outdoor samplers were initially considered for the LUR model. A set of GIS variables were constructed for traffic, land uses, population, urban configuration and elevation at all geographical sampling locations and they were offered in model development procedure. Several scenarios and model approaches were tested in order to achieve the best model performance. Those scenarios included removing specific tubes based on their location, for instance sites placed near street intersections. Statistic models tested included linear regression with interaction factors and spatial components. Standard validation tests such as normality, influential observations, heteroscedasticity and spatial autocorrelation were derived.

Health Impact Assessment

We estimated the asthma exposure on census tract level using the LUR model developed within the present study (see Figure 5). Population data for 2018 on census tract level for Barcelona was obtained from the national statistical records [129], and we selected the child population with an age equal or below 18 years old. Health data on asthma incidence rates

were collected for the specific age group (1-18 years old) for males and females in Spain from the Global Burden of Disease project [128]. A comparative health risk assessment approach was applied to estimate the number of asthma cases attributable to NO₂ [8, 10]. Two scenarios were created, scenario 1) achieving the average annual recommended guideline exposure levels for NO₂ (40 µg/m³) from the WHO guidelines [14]; and scenario 2) achieving the minimum reported levels of NO₂ (1.5 µg/m³) from a meta-analysis [9]. The exposure-response function between NO₂ and the development of asthma in children between the ages of 1 to 18 is based on 20 studies and equaled OR=1.05 (95% CI, 1.02 - 1.07) per each increment in the exposure to 4 µg/m³. This translates to a 5% increase in childhood asthma per 4 microgram/m³ increase in NO₂. The exposure-response function is used to estimate the relative risk (RR) of developing asthma for NO₂ and corresponding scenario by census tract. Then each RR is used to estimate the corresponding Population Attributable Fraction (PAF) for each scenario and pollutant. Finally, the PAF was combined with asthma cases, calculated for children between 1-18 years old in each census tract in Barcelona to estimate the attributable asthma cases for each level of exposure and census tract, and subsequently summed up to get a total for Barcelona.

Data availability

Data availability The NO₂ concentration level data that supports the findings of this study are available in Zenodo with the identifier, <https://doi.org/10.5281/zenodo.xxxxx> [PENDING].

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Author contributions

JP conceived the original idea for the citizen science xAire project; JP, JT, CD prepared the experimental setup; JP, IB, AC, JV, CD, JT performed the experiment; JP, JV, JT, AR, MC revised, calibrated, and analyzed the NO₂ concentration level data; MN, MC and DR performed the LUR model and the HIA; JP and AC analyzed the social impact of the xAire project; and all authors discussed the results, and wrote the paper.

Competing Interests statement

The authors declare no conflict of interest.

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- [1] World Health Organization. (2018). WHO global ambient air quality database (update 2018). World Health Organization: Geneva, Switzerland.
- [2] European Environmental Agency (2019). Air Quality in Europe – 2019 Report. European Environment Agency: No 10/2019.
- [3] Landrigan, P. J., Fuller, R., Acosta, N. J., Adeyi, O., Arnold, R., Baldé, A. B., ... & Chiles, T. (2018). The Lancet Commission on pollution and health. *The Lancet*, 391(10119), 462-512.
- [4] Nieuwenhuijsen, M. J. (2016). Urban and transport planning, environmental exposures and health-new concepts, methods and tools to improve health in cities. *Environmental health*, 15(1), S38.
- [5] Sunyer, J., Esnaola, M., Alvarez-Pedrerol, M., Forn, J., Rivas, I., López-Vicente, M., ... & Viana, M. (2015). Association between traffic-related air pollution in schools and cognitive development in primary school children: a prospective cohort study. *PLoS Med*, 12(3), e1001792.
- [6] Zhang, X., Chen, X., & Zhang, X. (2018). The impact of exposure to air pollution on cognitive performance. *Proceedings of the National Academy of Sciences*, 115(37), 9193-9197.
- [7] Carslaw, D. C. (2005). Evidence of an increasing NO₂/NO_x emissions ratio from road traffic emissions. *Atmospheric Environment*, 39(26), 4793-4802.
- [8] Rojas-Rueda, D., de Nazelle, A., Teixidó, O., & Nieuwenhuijsen, M. J. (2012). Replacing car trips by increasing bike and public transport in the greater Barcelona metropolitan area: a health impact assessment study. *Environment international*, 49, 100-109.
- [9] Khreis, H., et al., Exposure to Traffic-related Air Pollution and Risk of Development of Childhood Asthma: A Systematic Review and Meta-analysis. *Environment International*, 2017. 100: p. 1-31.
- [10] Pierangeli, I., Nieuwenhuijsen, M. J., Cirach, M., & Rojas-Rueda, D. (2020). Health equity and burden of childhood asthma-related to air pollution in Barcelona. *Environmental Research*, 109067.

- [11] Ajuntament de Barcelona. 2018. Dades bàsiques de mobilitat. Informe 2017.
- [12] <https://www.idescat.cat/emex/?id=080193>
- [13] Agència de Salut Pública de Barcelona. 2018. Avaluació de la Qualitat de l'Aire a la Ciutat de Barcelona. Informe 2017.
- [14] World Health Organization, W.H.O. Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide-Global update 2005-Summary of risk assessment, Geneva: WHO, 2006.
- [15] Síndic de Greuges de Catalunya. La qualitat de l'aire a Catalunya: dèficits i recomanacions. Juny 2019. http://www.sindic.cat/site/unitFiles/6328/Informe%20qualitat%20aire_cat_ok.pdf [Accessed 31st of August 2020]
- [16] Vardoulakis, S., Fisher, B. E., Pericleous, K., & Gonzalez-Flesca, N. (2003). Modelling air quality in street canyons: a review. *Atmospheric environment*, 37(2), 155-182.
- [17] Cyrus, J., Eeftens, M., Heinrich, J., Ampe, C., Armengaud, A., Beelen, R., ... & Cirach, M. (2012). Variation of NO₂ and NO_x concentrations between and within 36 European study areas: results from the ESCAPE study. *Atmospheric Environment*, 62, 374-390.
- [18] Wu, H., Reis, S., Lin, C., Beverland, I. J., & Heal, M. R. (2015). Identifying drivers for the intra-urban spatial variability of airborne particulate matter components and their interrelationships. *Atmospheric Environment*, 112, 306-316.
- [19] Lin, C., Feng, X., & Heal, M. R. (2016). Temporal persistence of intra-urban spatial contrasts in ambient NO₂, O₃ and O_x in Edinburgh, UK. *Atmospheric Pollution Research*, 7(4), 734-741.
- [20] Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe OJ L 152, 11.6.2008, p. 1-44.
- [21] Benavides, J., Snyder, M., Guevara, M., Soret, A., García-Pando, C. P., Amato, F., ... & Jorba, O. (2019). CALIOPE-Urban v1. 0: coupling R-LINE with a mesoscale air quality modelling system for urban air quality forecasts over Barcelona city (Spain). *Geoscientific Model Development*, 12(7), 2811-2835.
- [22] Vardoulakis, S., Gonzalez-Flesca, N., Fisher, B. E., & Pericleous, K. (2005). Spatial variability of air pollution in the vicinity of a permanent monitoring station in central Paris. *Atmospheric Environment*, 39(15), 2725-2736.
- [23] Hafkenscheid, T., Fromage-Marriette, A., Goelen, E., Hangartner, M., Pfeffer, U., Plaisance,

- H., & Gerboles, M. (2009). Review of the application of diffusive samplers for the measurement of nitrogen dioxide in ambient air in the European Union. Institute for Environment and Sustainability, Luxembourg: Office for Official Publications of the European Communities.
- [24] Santiago, J. L., Martín, F., & Martilli, A. (2013). A computational fluid dynamic modelling approach to assess the representativeness of urban monitoring stations. *Science of the total environment*, 454, 61-72.
- [25] Piersanti, A., Vitali, L., Righini, G., Cremona, G., & Ciancarella, L. (2015). Spatial representativeness of air quality monitoring stations: a grid model based approach. *Atmospheric Pollution Research*, 6(6), 953-960.
- [26] Borge, R., Lumberras, J., Pérez, J., de la Paz, D., Vedrenne, M., de Andrés, J. M., & Rodríguez, M. E. (2014). Emission inventories and modeling requirements for the development of air quality plans. Application to Madrid (Spain). *Science of the Total Environment*, 466, 809-819.
- [27] Duyzer, J., van den Hout, D., Zandveld, P., & van Ratingen, S. (2015). Representativeness of air quality monitoring networks. *Atmospheric Environment*, 104, 88-101.
- [28] Eurobarometer. (2019). Attitudes of Europeans towards Air Quality. Special Eurobarometer 497.
- [29] European Environment Agency (2019). Assessing air quality through citizen science. EEA Report No 19/2019.
- [30] Heigl, F., Kieslinger, B., Paul, K. T., Uhlik, J., & Dörler, D. (2019). Opinion: Toward an international definition of citizen science. *Proceedings of the National Academy of Sciences*, 116(17), 8089-8092.
- [31] Auerbach, J., Barthelmeß, E. L., Cavalier, D., Cooper, C. B., Fenyk, H., Haklay, M., ... & Shanley, L. (2019). The problem with delineating narrow criteria for citizen science. *Proceedings of the National Academy of Sciences*, 116(31), 15336-15337.
- [32] Parrish, J. K., Jones, T., Burgess, H. K., He, Y., Fortson, L., & Cavalier, D. (2019). Hoping for optimality or designing for inclusion: Persistence, learning, and the social network of citizen science. *Proceedings of the National Academy of Sciences*, 116(6), 1894-1901.
- [33] Jones, M. L., & Spiers, H. (2018). The crowd storms the ivory tower. *Nature methods*, 15(8), 579.
- [34] Irwin, A. (2018). No PhDs needed: How citizen science is transforming research. *Nature*,

562, 480-482.

- [35] Muki Haklay, *Citizen Science and Policy: A European Perspective*. Washington, DC: Woodrow Wilson International Center for Scholars, 2015. https://www.wilsoncenter.org/sites/default/files/Citizen_Science_Policy_European_Perspective_Haklay.pdf
- [36] Kosmala, M., Wiggins, A., Swanson, A., & Simmons, B. (2016). Assessing data quality in citizen science. *Frontiers in Ecology and the Environment*, 14(10), 551-560.
- [37] Guerrini, C. J., Majumder, M. A., Lewellyn, M. J., & McGuire, A. L. (2018). Citizen science, public policy. *Science*, 361(6398), 134-136.
- [38] MacDonald, E. A., Donovan, E., Nishimura, Y., Case, N. A., Gillies, D. M., Gallardo-Lacourt, B., ... & Heavner, M. (2018). New science in plain sight: Citizen scientists lead to the discovery of optical structure in the upper atmosphere. *Science advances*, 4(3), eaaq0030.
- [39] Lukyanenko, R., Wiggins, A., & Rosser, H. K. (2019). Citizen science: An information quality research frontier. *Information Systems Frontiers*, 1-23.
- [40] Shanley, L. A., Parker, A., Schade, S., & Bonn, A. (2019). Policy Perspectives on Citizen Science and Crowdsourcing. *Citizen Science: Theory and Practice*, 4(1).
- [41] Hecker, S., Wicke, N., Haklay, M., & Bonn, A. (2019). How Does Policy Conceptualise Citizen Science? A Qualitative Content Analysis of International Policy Documents. *Citizen Science: Theory and Practice*, 4(1).
- [42] Fritz, S., See, L., Carlson, T., Haklay, M. M., Oliver, J. L., Fraisl, D., ... & Wehn, U. (2019). Citizen science and the United Nations Sustainable Development Goals. *Nature Sustainability*, 2(10), 922-930.
- [43] Koepnick, B., Flatten, J., Husain, T., Ford, A., Silva, D. A., Bick, M. J., ... & Estep, R. D. (2019). De novo protein design by citizen scientists. *Nature*, 570(7761), 390-394.
- [44] Mehr, S. A., Singh, M., Knox, D., Ketter, D. M., Pickens-Jones, D., Atwood, S., ... & Howard, R. M. (2019). Universality and diversity in human song. *Science*, 366(6468).
- [45] Fairclough, D. V., Brown, J. I., Carlish, B. J., Crisafulli, B. M., & Keay, I. S. (2014). Breathing life into fisheries stock assessments with citizen science. *Scientific reports*, 4, 7249.
- [46] Schuster, R., Wilson, S., Rodewald, A. D., Arcese, P., Fink, D., Auer, T., & Bennett, J. R. (2019). Optimizing the conservation of migratory species over their full annual cycle. *Nature communications*, 10(1), 1754.
- [47] Miller, E. T., Leighton, G. M., Freeman, B. G., Lees, A. C., & Ligon, R. A. (2019). Ecolog-

- ical and geographical overlap drive plumage evolution and mimicry in woodpeckers. *Nature communications*, 10(1), 1602.
- [48] Jetz, W., McGeoch, M. A., Guralnick, R., Ferrier, S., Beck, J., Costello, M. J., ... & Meyer, C. (2019). Essential biodiversity variables for mapping and monitoring species populations. *Nature ecology & evolution*.
- [49] Johnson, B. J., Brosch, D., Christiansen, A., Wells, E., Wells, M., Bhandoola, A. F., ... & Fonseca, D. M. (2018). Neighbors help neighbors control urban mosquitoes. *Scientific reports*, 8(1), 15797.
- [50] Palmer, J. R., Oltra, A., Collantes, F., Delgado, J. A., Lucientes, J., Delacour, S., ... & Bartumeus, F. (2017). Citizen science provides a reliable and scalable tool to track disease-carrying mosquitoes. *Nature communications*, 8(1), 916.
- [51] Garcia-Martí, I., Zurita-Milla, R., Harms, M. G., & Swart, A. (2018). Using volunteered observations to map human exposure to ticks. *Scientific reports*, 8(1), 15435.
- [52] Gutiérrez-Roig, M., Sagarra, O., Oltra, A., Palmer, J. R., Bartumeus, F., Díaz-Guilera, A., & Perelló, J. (2016). Active and reactive behaviour in human mobility: the influence of attraction points on pedestrians. *Royal Society open science*, 3(7), 160177.
- [53] Steed, R. J., Fuenzalida, A., Bossu, R., Bondár, I., Heinloo, A., Dupont, A., ... & Strollo, A. (2019). Crowdsourcing triggers rapid, reliable earthquake locations. *Science advances*, 5(4), eaau9824.
- [54] Dutta, P., Aoki, P. M., Kumar, N., Mainwaring, A., Myers, C., Willett, W., & Woodruff, A. (2009, November). Common sense: participatory urban sensing using a network of handheld air quality monitors. In *Proceedings of the 7th ACM conference on embedded networked sensor systems* (pp. 349-350).
- [55] Kumar, P., Morawska, L., Martani, C., Biskos, G., Neophytou, M., Di Sabatino, S., ... & Britter, R. (2015). The rise of low-cost sensing for managing air pollution in cities. *Environment international*, 75, 199-205.
- [56] Clements, A. L., Griswold, W. G., Rs, A., Johnston, J. E., Herting, M. M., Thorson, J., ... & Hannigan, M. (2017). Low-cost air quality monitoring tools: from research to practice (a workshop summary). *Sensors*, 17(11), 2478.
- [57] Castell, N., Dauge, F. R., Schneider, P., Vogt, M., Lerner, U., Fishbain, B., ... & Bartonova, A. (2017). Can commercial low-cost sensor platforms contribute to air quality monitoring

- and exposure estimates?. *Environment international*, 99, 293-302.
- [58] Jerrett, M., Donaire-Gonzalez, D., Popoola, O., Jones, R., Cohen, R. C., Almanza, E., ... & Triguero-Mas, M. (2017). Validating novel air pollution sensors to improve exposure estimates for epidemiological analyses and citizen science. *Environmental research*, 158, 286-294.
- [59] Mijling, B., Jiang, Q., De Jonge, D., & Bocconi, S. (2018). Field calibration of electrochemical NO₂ sensors in a citizen science context. *Atmospheric Measurement Techniques*, 11(3), 1297-1312.
- [60] Ripoll, A., Viana, M., Padrosa, M., Querol, X., Minutolo, A., Hou, K. M., ... & García-Vidal, J. (2019). Testing the performance of sensors for ozone pollution monitoring in a citizen science approach. *Science of the total environment*, 651, 1166-1179.
- [61] Languille, B., Gros, V., Bonnaire, N., Pommier, C., Honoré, C., Debert, C., ... & Zeitouni, K. (2020). A methodology for the characterization of portable sensors for air quality measure with the goal of deployment in citizen science. *Science of the Total Environment*, 708, 134698.
- [62] Caplin, A., Ghandehari, M., Lim, C., Glimcher, P., & Thurston, G. (2019). Advancing environmental exposure assessment science to benefit society. *Nature communications*, 10(1), 1236.
- [63] Wesseling, J., de Ruiter, H., Blokhuis, C., Drukker, D., Weijers, E., Volten, H., ... & van Ratingen, S. (2019). Development and implementation of a platform for public information on air quality, sensor measurements, and citizen science. *Atmosphere*, 10(8), 445.
- [64] De Craemer, S., Vercauteren, J., Fierens, F., Lefebvre, W., & Meysman, F. (2020, April 21). Using large-scale NO₂ data from citizen science for air quality compliance and policy support. <https://doi.org/10.31223/osf.io/ft7mr>
- [65] Longo, A., Zappatore, M., & Bochicchio, M. A. (2020). Apollon: Towards a citizen science methodology for urban environmental monitoring. *Future Generation Computer Systems*.
- [66] Chen, L. J., Ho, Y. H., Lee, H. C., Wu, H. C., Liu, H. M., Hsieh, H. H., ... & Lung, S. C. C. (2017). An open framework for participatory PM_{2.5} monitoring in smart cities. *IEEE Access*, 5, 14441-14454.
- [67] Haklay, M., & Eleta, I. (2019). On the front line of community-led air quality monitoring. In *Integrating Human Health into Urban and Transport Planning* (pp. 563-580). Springer, Cham.
- [68] English, P. B. et al. The Imperial County Community Air Monitoring Network: a model

- for community-based environmental monitoring for public health action. *Environ. Health Perspect.* 125, 074501 (2017).
- [69] Hsu, Y. C., Dille, P., Cross, J., Dias, B., Sargent, R., & Nourbakhsh, I. (2017, May). Community-empowered air quality monitoring system. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (pp. 1607-1619).
- [70] Castell, N., Kobernus, M., Liu, H. Y., Schneider, P., Lahoz, W., Berre, A. J., & Noll, J. (2015). Mobile technologies and services for environmental monitoring: The Citi-Sense-MOB approach. *Urban climate*, 14, 370-382.
- [71] Van den Bossche, J., Theunis, J., Elen, B., Peters, J., Botteldooren, D., & De Baets, B. (2016). Opportunistic mobile air pollution monitoring: a case study with city wardens in Antwerp. *Atmospheric environment*, 141, 408-421.
- [72] Yang, L., Li, W., Ghandehari, M., & Fortino, G. (2017). People-centric cognitive internet of things for the quantitative analysis of environmental exposure. *IEEE Internet of Things Journal*, 5(4), 2353-2366.
- [73] Schaefer, T., Kieslinger, B., & Fabian, C. M. (2020). Citizen-Based Air Quality Monitoring: The Impact on Individual Citizen Scientists and How to Leverage the Benefits to Affect Whole Regions. *Citizen Science: Theory and Practice*, 5(1).
- [74] Golumbic, Y. N., Fishbain, B., & Baram-Tsabari, A. (2019). User centered design of a citizen science air-quality monitoring project. *International Journal of Science Education, Part B*, 9(3), 195-213.
- [75] Mahajan, S., Kumar, P., Pinto, J. A., Riccetti, A., Schaaf, K., Camprodon, G., ... & Forino, G. (2020). A citizen science approach for enhancing public understanding of air pollution. *Sustainable Cities and Society*, 52, 101800.
- [76] Van Brussel, S., & Huyse, H. (2019). Citizen science on speed? Realising the triple objective of scientific rigour, policy influence and deep citizen engagement in a large-scale citizen science project on ambient air quality in Antwerp. *Journal of Environmental Planning and Management*, 62(3), 534-551.
- [77] Kloetzer, L., Jennett, C., Francis, L., & Haklay, M. (2017). Community Engagement Around Poor Air Quality in London: Citizen inquiry in a citizen science “Mapping for Change” project. In *Citizen Inquiry* (pp. 42-62). Routledge.
- [78] Palmes, E. D., Gunnison, A. F., DiMattio, J., & Tomczyk, C. (1976). Personal sampler for

- nitrogen dioxide. *American Industrial Hygiene Association Journal*, 37(10), 570-577.
- [79] Sagarra, O., Gutiérrez-Roig, M., Bonhoure, I., & Perelló, J. (2016). Citizen science practices for computational social science research: The conceptualization of pop-up experiments. *Frontiers in physics*, 3, 93.
- [80] Perelló, J., Murray-Rust, D., Nowak, A., & Bishop, S. R. (2012). Linking science and arts: Intimate science, shared spaces and living experiments. *The European Physical Journal Special Topics*, 214(1), 597-634.
- [81] Steiner, S.M. (2020). Popular Epidemiology and Community-Based Citizen Science: Using a Bio-Indicator for Toxic Air Pollution. *SAGE Research Methods Cases*. doi:10.4135/9781529710748.
- [82] Perelló, J., Targa, J., Daher, C., Alonso, M., & Masha-Caminals, A.. (2018, February 11). X Aire. Guia d'ús per a centres educatius. Zenodo. <http://doi.org/10.5281/zenodo.3718949>
- [83] Visit the website: <http://xaire.communitymaps.org.uk>
- [84] InfoK. (2018, 28 February) Mesurem la qualitat de l'aire de Barcelona <https://www.ccma.cat/video/embed/super3/5734607/> (Video: 1m49s) [Retrieved 9th of March 2020]
- [85] Vallejo, O. (2018, 29 Oct) xAire mesura la qualitat de l'aire. Diari ARA. Suplement Criatures. https://criatures.ara.cat/escola/Xaire-mesura-qualitat-aire-projecte-escoles_0_2097390254.html [Retrieved 9th of March 2020]
- [86] Ryan, P.H., LeMasters, G.K., 2007. A review of land-use regression models for characterizing intraurban air pollution exposure. *Inhalation Toxicology* 19 (Suppl. 1), 127e133.
- [87] Hoek, G., Beelen, R., De Hoogh, K., Vienneau, D., Gulliver, J., Fischer, P., & Briggs, D. (2008). A review of land-use regression models to assess spatial variation of outdoor air pollution. *Atmospheric environment*, 42(33), 7561-7578.
- [88] Local Air Quality Management Technical Guidance (TG16) 2018. Department for Environment, Food and Rural Affairs, London, United Kingdom.
- [89] Tiago, P., Ceia-Hasse, A., Marques, T. A., Capinha, C., & Pereira, H. M. (2017). Spatial distribution of citizen science casuistic observations for different taxonomic groups. *Scientific reports*, 7(1), 12832.
- [90] Kallimanis, A. S., Panitsa, M., & Dimopoulos, P. (2017). Quality of non-expert citizen science data collected for habitat type conservation status assessment in Natura 2000 protected areas.

- Scientific reports, 7(1), 8873.
- [91] Dumas, P., Fiat, S., Durbano, A., Peignon, C., Mou-Tham, G., Ham, J., ... & Antoine De Ramon, N. Y. (2020). Citizen Science, a promising tool for detecting and monitoring outbreaks of the crown-of-thorns starfish *Acanthaster* spp. *Scientific Reports*, 10(1), 1-10.
- [92] Ajuntament de Barcelona. Departament d'Estadística i Difusió de Dades. Lectura del Padró Municipal d'Habitants a 1 gener 2018. <https://www.bcn.cat/estadistica/catala/dades/tpob/pad/padro/a2018/llocna/llocna11.htm> [Accessed 7 September 2020].
- [93] INE. Renda tributària mitjana per persona de la ciutat de Barcelona en base al projecte experimental Atlas de distribució de la renda de les llars de l'Institut Nacional d'Estadística (INE). <https://opendata-ajuntament.barcelona.cat/data/ca/dataset/renda-tributaria-per-persona-atlas-distribucio/resource/d6bb4f5e-d719-447d-b6e8-5e3be2f710f2> [Accessed 7 September 2020].
- [94] Eeftens, M., Tsai, M. Y., Ampe, C., Anwander, B., Beelen, R., Bellander, T., ... & De Nazelle, A. (2012). Spatial variation of PM_{2.5}, PM₁₀, PM_{2.5} absorbance and PM_{coarse} concentrations between and within 20 European study areas and the relationship with NO₂—results of the ESCAPE project. *Atmospheric Environment*, 62, 303-317.
- [95] ESCAPE (European Study of Cohorts for Air Pollution Effects). 2013. Manuals. Available: <http://www.escapeproject.eu/manuals/> [accessed 20 December 2019].
- [96] Basagaña, X., Rivera, M., Aguilera, I., Agis, D., Bouso, L., Elosua, R., ... & Künzli, N. (2012). Effect of the number of measurement sites on land use regression models in estimating local air pollution. *Atmospheric environment*, 54, 634-642.
- [97] Johnson, M., Isakov, V., Touma, J.S., Mukerjee, S., Özkaynak, H., 2010. Evaluation of land-use regression models used to predict air quality concentrations in an urban area. *Atmospheric Environment* 44, 3660e3668.
- [98] Consorci d'Educació de Barcelona (2018, 22 May). Com afecta el trànsit a la qualitat de l'aire que ens envolta? Streaming recording of kids' presentations in 5th Science Congress (In Catalan). Escola El Sagrer. <https://youtu.be/4FByPK3QKA0> [Retrieved 28th of July 2020]
- [99] Consorci d'Educació de Barcelona (2018, 23 May) Per què des del Tibidabo a vegades no veiem el mar? Streaming recording of kids' presentations in 5th Science Congress (In Cata-

- lan). Escola Joan Miró. <https://youtu.be/NdllbLYxdFs> [Retrieved 28th of July 2020]
- [100] xAire. (2020, March 6). Monitoratge de la qualitat de l'aire a Barcelona - Presentació resultats de les escoles participants. Zenodo. <http://doi.org/10.5281/zenodo.3699613>
- [101] Consorci d'Educació de Barcelona (2018, 22 May). Com evolucionaria un ecosistema en equilibri ecològic per l'augment de la temperatura del planeta? Streaming recording of kids' presentations in 5th Science Congress (In Catalan). Escola Dolors Monserdà Santa Pau. <https://youtu.be/piYM6wv2v04> [Retrieved 28th of July 2020]
- [102] Consorci d'Educació de Barcelona (2018, 24 May). Com és l'aire que respirem al nostre barri? Streaming recording of kids' presentations in 5th Science Congress (In Catalan) Escola SEAT <https://youtu.be/B60crEVfpXc> [Retrieved 28th of July 2020]
- [103] Consorci d'Educació de Barcelona (2018, 24 May). Com és l'aire que respirem en els nostres camins a l'escola? (Estudi de la concentració de diòxid de nitrogen al nostre barri). Streaming recording of kids' presentations in 5th Science Congress (In Catalan) Escola Sagrada Família. https://youtu.be/j6gTkHHq_C4 [Retrieved 28th of July 2020]
- [104] Consorci d'Educació de Barcelona (2018, 24 May). Com podem saber si la qualitat de l'aire que respirem al nostre barri és bona? Streaming recording of kids' presentations in 5th Science Congress (In Catalan) Escola Els Horts <https://youtu.be/gxNXgYWQ3TU> [Retrieved 28th of July 2020]
- [105] Consorci d'Educació de Barcelona (2018, 23 May). Streaming recording of kids' presentations in 5th Science Congress (In Catalan) Escola Pau Casals Gràcia <https://youtu.be/0b4FO2QRoZQ> [Retrieved 28th of July 2020]
- [106] Consorci d'Educació de Barcelona (2018, 24 May). Com podem millorar la qualitat de l'aire a la nostra escola? Streaming recording of kids' presentations in 5th Science Congress (In Catalan) Escola Timbaler del Bruc <https://youtu.be/P2BEymW-QNQ> [Retrieved 28th of July 2020]
- [107] Consorci d'Educació de Barcelona (2018, 23 May). Streaming recording of kids' presentations in 5th Science Congress (In Catalan) Escola Can Fabra https://youtu.be/_F9dz2XGOGQ [Retrieved 28th of July 2020]
- [108] Consorci d'Educació de Barcelona (2018, 24 May). Com és que l'Ajuntament de Bcn vol limitar la circulació d'alguns vehicles dins de la ciutat durant alguns dies concrets? Streaming recording of kids' presentations in 5th Science Congress (In Catalan) Escola Fort Pienc

- <https://youtu.be/3aNKTrwONFO> [Retrieved 28th of July 2020]
- [109] Sauermann, H., Vohland, K., Antoniou, V., Balázs, B., Göbel, C., Karatzas, K., ... & Winter, S. (2020). Citizen science and sustainability transitions. *Research Policy*, 49(5), 103978.
- [110] Benedetti, Y., Slezak, K., Møller, A. P., Morelli, F., & Tryjanowski, P. (2018). Number of syllables in cuckoo *Cuculus canorus* calls: A test using a citizen science project. *Scientific reports*, 8(1), 12872.
- [111] West, S. E., Büker, P., Ashmore, M., Njoroge, G., Welden, N., Muhoza, C., ... & Apondo, W. (2020). Particulate matter pollution in an informal settlement in Nairobi: Using citizen science to make the invisible visible. *Applied Geography*, 114, 102133.
- [112] Stern, P. C. (2000). New environmental theories: toward a coherent theory of environmentally significant behavior. *Journal of social issues*, 56(3), 407-424.
- [113] Bio Innovation Service. (2018). Citizen science for environmental policy: development of an EU-wide inventory and analysis of selected practices. Final report for the European Commission, DG Environment under the contract 070203/2017/768879/ETU/ENV.A.3, in collaboration with Fundacion Ibercivis and The Natural History Museum, November 2018.
- [114] USEPA. (2016). Environmental Protection Belongs to the Public: A Vision for Citizen Science at EPA. Accessed March 6 2020 https://www.epa.gov/sites/production/files/2016-12/documents/nacept_cs_report_final_508_0.pdf
- [115] Johnson, M. F., Hannah, C., Acton, L., Popovici, R., Karanth, K. K., & Weinthal, E. (2014). Network environmentalism: Citizen scientists as agents for environmental advocacy. *Global Environmental Change*, 29, 235-245.
- [116] Haywood, B. K., Parrish, J. K., & Dolliver, J. (2016). Place-based and data-rich citizen science as a precursor for conservation action. *Conservation Biology*, 30(3), 476-486.
- [117] Jordan, R. C., Sorensen, A. E., Biehler, D., Wilson, S., & LaDeau, S. (2019). Citizen science and civic ecology: Merging paths to stewardship. *Journal of Environmental Studies and Sciences*, 9(1), 133-143.
- [118] Bonney, R., Phillips, T. B., Ballard, H. L., & Enck, J. W. (2016). Can citizen science enhance public understanding of science?. *Public Understanding of Science*, 25(1), 2-16.
- [119] Perelló J., Ferran-Ferrer N., Ferré S., Pou T. & Bonhoure I. (2017) High motivation and relevant scientific competencies through the introduction of citizen science at Secondary schools. In: Herodotou C., Sharples M. and Scanlon E. (eds) (2017) *Citizen inquiry: synthesising*

- science and inquiry learning*. London: Routledge pp.150–175.
- [120] Senabre, E., Ferran-Ferrer, N., & Perelló, J. (2018). Participatory design of citizen science experiments. *Comunicar. Media Education Research Journal*, 26(1).
- [121] https://www.miteco.gob.es/es/calidad-y-evaluacion-ambiental/temas/atmosfera-y-calidad-del-aire/cleanairschools-girona-2019_tcm30-509918.pdf
[Retrieved 29th of July 2020]
- [122] Kullenberg, C. (2015). Citizen science as resistance: Crossing the boundary between reference and representation. *Journal of Resistance Studies*, 1(1), 50-76.
- [123] Berti Suman, A., & van Geenhuizen, M. (2019). Not just noise monitoring: rethinking citizen sensing for risk-related problem-solving. *Journal of Environmental Planning and Management*, 1-22.
- [124] Website of the Science Congress (Congrés de Ciència, in Catalan) <https://sites.google.com/site/5econgresstreaming>
- [125] Ajuntament de Barcelona (2018, 26 April) Barcelona schoolchildren gather data on the city's air quality https://ciutatrefugi.barcelona/en/noticia/barcelona-schoolchildren-gather-data-on-the-citys-air-quality_647956 [Retrieved 9th of March 2020]
- [126] Targa, J., & Loader, A. (2008). Diffusion tubes for ambient NO₂ monitoring: practical guidance for laboratories and users. Report to Defra and the Devolved Administrations. AEA Energy & Environment, Harwell.
- [127] Kuklinska, K., Wolska, L., & Namiesnik, J. (2015). Air quality policy in the US and the EU—a review. *Atmospheric Pollution Research*, 6(1), 129-137.
- [128] Global Burden of Disease Collaborative Network. Global Burden of Disease Study 2016 (GBD 2016) Results. Seattle, United States: Institute for Health Metrics and Evaluation (IHME), 2017.
- [129] Instituto Nacional de Estadística, 2011. Censos de Población y Viviendas 2011. Resultados Nacionales, por Comunidades Autónomas y Provincias.

Supplementary Information

Supplementary Figures

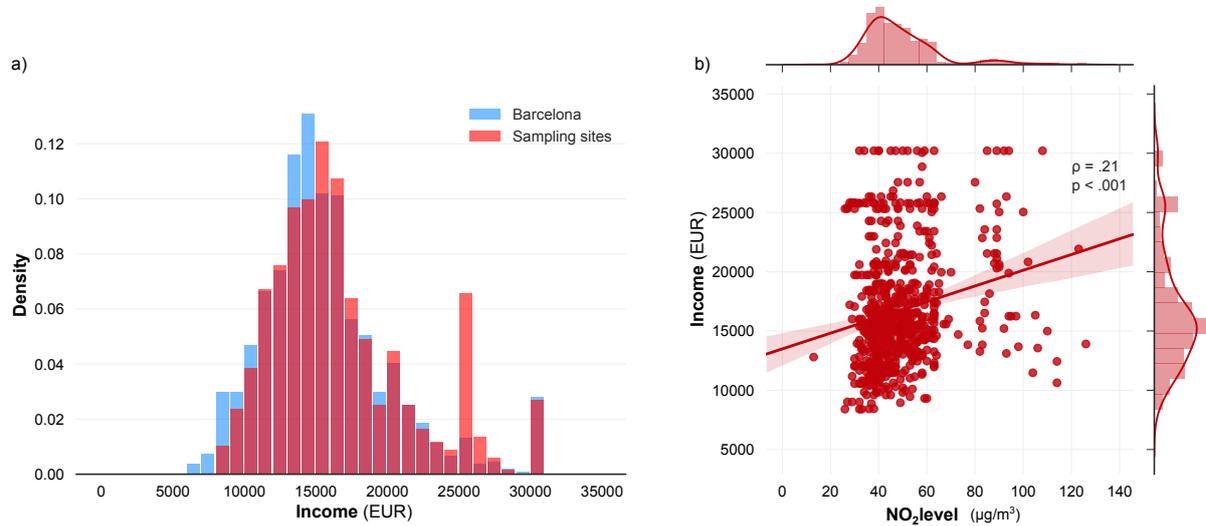


FIG. S1: **Samplers distribution and income distribution.** (a) Distributions of income (red, in Euros, $n=1,068$) and distribution of samplers (blue, $n=671$, per unit of census tract). (b) Scatter plot between NO₂ concentration levels and income average in each census tract (Pearson's $r=0.21$, $p\text{-value}=3.93e-08$). See Table S4 for detailed statistical traits.

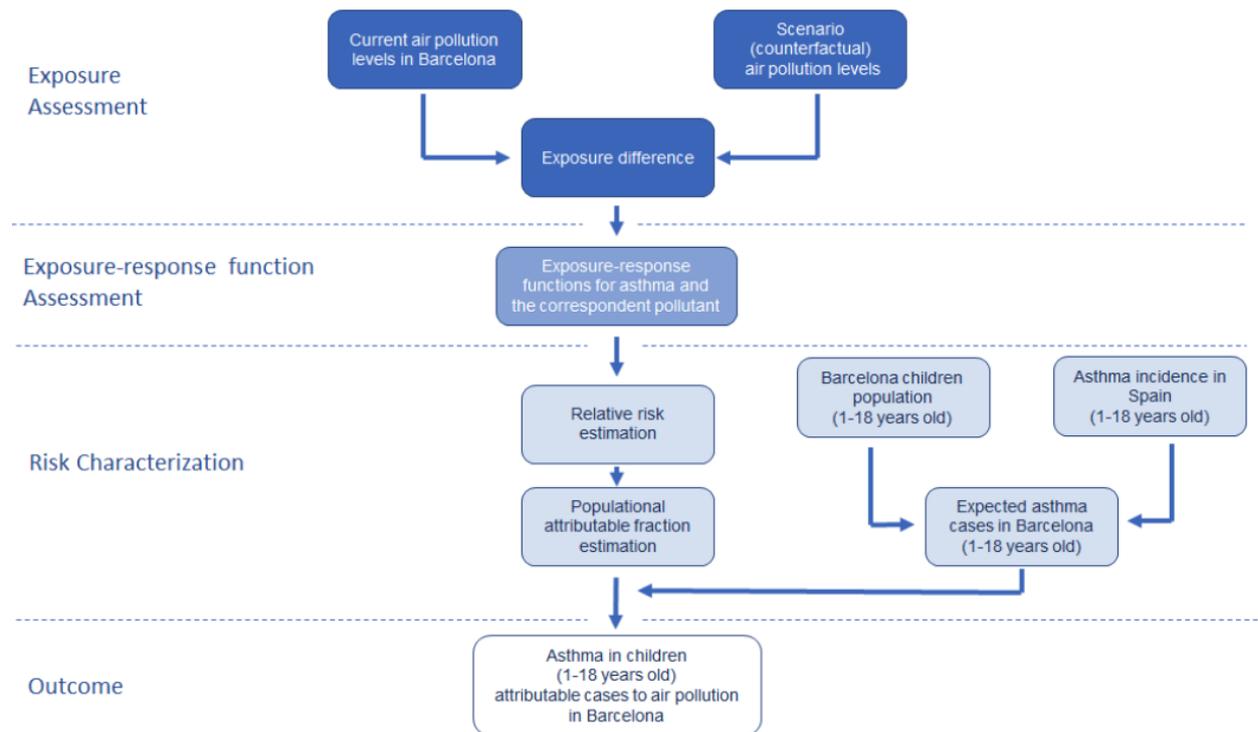


FIG. S2: **Quantitative health impact assessment framework.** It is been used to estimate the attributable asthma cases related to air pollution in Barcelona by scenario.

Supplementary Tables

	n	mean	sem	SD	median	5%	25%	75%	95%	skew	kurt
Aggregated	725	48	1	16	44	30	38	54	84	1.72	4.17
Outdoor	671	49	1	16	45	32	39	55	85	1.82	4.30
Traffic	482	52	1	16	49	34	42	58	89	1.68	3.34
Background	189	41	1	9	39	30	36	44	56	1.81	9.01
Playground	31	37	1	7	38	28	34	40	49	0.18	0.37
Indoor	23	31	3	14	28	18	24	36	51	2.43	7.97

TABLE S1: **General statistics of the NO₂ concentration levels of the xAire project depending on their location.** Consistent rounding is provided grounded on sampler’s precision and accuracy (see Methods, Data precision and accuracy). First column provides the number of samplers. Second and third column the average jointly with the standard error of the mean (sem). Fourth column provides the standard deviation (SD). Given the fact that data has relevant skewness (skew, 11th column) and kurtosis (kurt, 12th column), it is relevant to provide 5% percentile (5% of the samplers have a lower concentration level than the score), first quartile (25% of the samplers have a lower concentration level than the score sixth column), median (sixth column) and third quartile (25% of the samplers have a greater concentration level than the score), and 95% percentile (95% of the samplers have a lower concentration level than the score). Concentration levels are provided in $\mu\text{g}/\text{m}^3$.

district	n	mean	median	sem	std	5%	25%	75%	95%	skew	kurt
Ciutat Vella	53	51	46	17	2	37	41	54	94	2.49	1.82
L'Eixample	134	57	55	15	1	40	47	63	89	0.38	1.04
Gràcia	64	46	43	12	2	34	38	51	62	8.86	2.54
Horta-Guinardó	61	42	38	15	2	32	35	44	58	13.49	3.52
Les Corts	56	47	44	10	1	34	40	53	63	3.35	1.34
Nou Barris	58	43	39	15	2	29	36	49	63	15.92	3.29
Sant Andreu	71	48	47	13	1	36	42	52	61	12.50	3.07
Sant Martí	64	41	39	9	1	30	34	46	57	0.35	0.08
Sants-Montjuïc	44	49	46	11	2	38	41	57	64	1.04	1.12
Sarrià-Sant Gervasi	66	54	48	22	3	28	38	63	94	0.52	1.10

TABLE S2: **Statistics of the NO₂ concentration levels of the xAire project in terms of the district** Consistent rounding grounded on sampler's precision and accuracy (see Methods, Data precision and accuracy) is provided. The same description of the columns as in Table S1 applies. Concentration levels are provided in $\mu\text{g}/\text{m}^3$.

district	type	n	mean	median	sem	SD	5%	25%	75%	95%	skew	kurt
Ciutat Vella	background	36	46	45	11	2	35	40	48	57	11.90	2.99
	traffic	17	63	56	22	5	41	46	82	97	-0.98	0.74
L'Eixample	background	17	45	42	9	2	38	39	48	66	1.36	1.56
	traffic	117	59	56	15	1	42	49	63	89	0.24	1.04
Gràcia	background	15	41	38	9	2	32	35	42	58	0.14	1.15
	traffic	49	48	46	13	2	36	40	52	62	8.92	2.71
Horta-Guinardó	background	26	37	37	5	1	30	33	39	45	-0.60	0.23
	traffic	35	46	39	19	3	33	37	50	85	6.92	2.69
Les Corts	background	21	41	40	6	1	32	37	43	51	1.05	1.02
	traffic	35	51	49	11	2	38	44	55	63	3.33	1.27
Nou Barris	background	14	35	37	5	1	27	33	38	41	-0.27	-0.33
	traffic	44	46	43	16	2	32	37	52	63	13.50	3.10
Sant Andreu	background	9	40	36	8	3	33	36	46	52	-0.18	0.92
	traffic	62	49	47	13	2	39	42	52	62	12.38	3.19
Sant Martí	background	21	36	37	8	2	28	33	40	45	2.09	-0.76
	traffic	43	43	42	9	1	32	36	50	58	-1.01	0.36
Sants-Montjuïc	background	15	44	41	6	2	38	40	50	55	-0.84	0.85
	traffic	29	52	53	11	2	39	43	59	72	0.37	0.87
Sarrià-Sant Gervasi	background	15	38	36	10	3	27	30	42	53	0.91	1.12
	traffic	51	58	52	23	3	32	41	65	98	-0.00	0.90

TABLE S3: **Statistics of the NO₂ concentration levels of the xAire project in terms of the district and in terms of the type of location (background and traffic)** Sampler's precision and accuracy is described in Methods, Data precision and accuracy. The same description of each column as in Table S2 applies. Concentration levels are provided in $\mu\text{g}/\text{m}^3$.

Population spatial distribution per census tract (in inhabitants)											
	n	mean	sem	SD	median	5%	25%	75%	95%	skew	kurt
Barcelona	1068	1525	11	358	1484	1072	1270	1692	2167	1.38	3.94
xAire	671	1556	15	383	1504	1139	1271	1727	2435	1.60	4.52
Averaged Income spatial distribution per census tract (in EUR)											
	n	mean	sem	SD	median	5%	25%	75%	95%	skew	kurt
Barcelona	1068	15726	140	4583	14977	9330	12906	17637	25259	1.07	1.55
xAire	671	16737	189	4886	15664	10558	13286	18950	25829	0.91	0.31

TABLE S4: **Comparison between population and income spatial distributions per census tract.** In each case, the Barcelona data [92, 93] is provided to evaluate the representativeness of the xAire citizen science site selection. First column provides the number of samplers. Second column the average. Third is the Standard Error of the Mean while fourth column is the standard deviation (SD). Next columns provide the 5%, 25% (Q1, 1st Quartile), 75% (Q3, 3rd Quartile) and the 95% percentiles. The scores give the value below which 5%, 25%, 75%, and 95% of the observations may be found. Skewness and Kurtosis are provided in the last couple of columns. See also Figs. 4 and S1.