Local Environment
The International Journal of Justice and Sustainability

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/cloe20

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To cite this article: Douglas Booker, Gordon Walker, Paul J. Young & Ana Porroche-Escudero (2023) A critical air quality science perspective on citizen science in action, Local Environment, 28:1, 31-46, DOI: 10.1080/13549839.2022.2118700

To link to this article: https://doi.org/10.1080/13549839.2022.2118700

Published online: 13 Sep 2022.

LOCAL ENVIRONMENT
2023, VOL. 28, NO. 1, 31–46
https://doi.org/10.1080/13549839.2022.2118700

Routledge
Taylor & Francis Group

A critical air quality science perspective on citizen science in action

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ABSTRACT

Air pollution is a hybrid phenomenon, understood and produced through social practices and material environmental processes. This hybridity leads us to engage critically with how air quality science is carried out. In dialogue with the critical physical geography subdiscipline, we propose a critical air quality science (CAQS) framework to study air pollution's sociomateriality. We use CAQS to illuminate four tensions in the dynamics of knowledge production during a citizen science air quality monitoring project: making undone science matter, blurring "insiderness"/"outsiderness", traffic as both life and death, and changing behaviours versus changing systems. Drawing on interviews with citizen scientists, we outline the implications of these tensions for air quality research design and reporting. The CAQS framework provokes critical thought about the consequences of how air quality science understands, creates and communicates knowledge, and how we can reconfigure our relations with the air to minimise air inequalities.

ARTICLE HISTORY
Received 17 March 2022
Accepted 9 August 2022

KEYWORDS
Air pollution; air quality; citizen science; critical air quality science; environmental justice; epistemic justice

Established knowledge on air pollution's material properties and effects has been vital in the development of guidelines and regulations aimed at improving air quality (e.g. WHO 2021). While this knowledge is important, it has not resolved the question of what poor air quality is, how it manifests, or how it can be known. This is because air pollution's materiality is not self-evident: it is a "hybrid" entity, produced through social practices and material environmental processes, known in ways that are socially defined by different actors, and not only revealed through applying standard scientific methods and assessments (Cupples 2009).

Embracing air pollution as a hybrid phenomenon requires us to rethink how we come to understand it and to reflect on the epistemic boundaries that are established in air pollution knowledge production. Challenges to the relevance of dominant forms of air pollution knowledge, and mobilisation of claims of epistemic injustice (Fricker 2007), have come from community groups suffering from air pollution. Whether exposed to short-term "spikes" of air pollution that are averaged out by regulators (Ottinger and Sarantschin 2017), or having higher rates of asthma in the neighbourhood that have not yet been linked to air pollution (Brown et al. 2003), community groups have questioned the data of governmental or industrial monitoring regimes (e.g. Gabrys, Pritchard, and Barratt 2016; Ottinger 2010). They sought to remedy "undone science" – a concept that has been mobilised to refer to areas of research that are left unfunded, incomplete, or ignored (Frickel et al. 2010) – by generating their own data. In so doing community groups often collaborate with

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experts to access their knowledge and skills, including the use of air quality monitoring equipment, contributions to data interpretation, and allyship in campaigning for change (e.g. Gabrys, Pritchard, and Barratt 2016; Ottinger 2010). However, research has shown that citizens can understand and use air quality data differently to traditional air quality experts (Bickerstaff 2004; Gabrys, Pritchard, and Barratt 2016; Ottinger 2010). This creates tensions around the appropriate form of expertise that "sympathetic" scientists should provide and the processes through which their collaborations with citizens and communities should be enacted.

It is at this nexus that we explore air quality research that acknowledges air pollution's material significance and also embraces its hybridity and multiplicity (Cupples 2009; Garnett 2017), culminating in an approach that we call critical air quality science (CAQS). We combine this theoretical argument with a constructivist approach to understand how people make sense of the air and ascribe it meaning (Bickerstaff and Walker 2003), drawing on both semi-structured interviews with members of the community group "Better Old Swan" based in Liverpool, UK, and our own reflections – as academics and technical experts – involved in this group's citizen science project on air pollution. We ruminate on CAQS in practice, interrogating the contestations, contradictions and dilemmas that arose during this project, by opening up four tensions: (1) the challenges involved in making citizen-generated air quality data matter in policy and practice, especially as the project went beyond the dominant paradigm of regulatory air quality monitoring practice; (2) the construction and contestation of "insider–outsider" designations and their implications for the design and reporting of air quality research; (3) the potential unintended sociomaterial impacts of air quality research, including the dilemmas raised when communicating its results; and (4) the dilemma as to whether to focus on short-term goals to reduce air pollution exposure through behavioural changes, or longer-term goals that address the structural causes of air pollution. We discuss the implications of these tensions for the practice of CAQS and reflect on how to address them when undertaking future CAQS work. Before focusing on the case study analysis, we begin by laying out the body of previous work that has provided inspiration for the notion of CAQS.

Constructing a critical air quality science

Approaches to integrating the social and natural sciences have a long history. While this has included air quality science specifically (e.g. Cupples 2009), much air quality research remains in disciplinary silos based on problematic dichotomies between nature and society, despite it "not [being] immediately clear whether air pollution belongs to nature or to culture" (Cupples 2009, 211). Humans have always manipulated the air around them, such as by fire or exhaled viral particles. Moreover, the way that we describe the air is entangled in our own values (Cronon 1996). For example, air quality science is "motivated in large part by a desire to purify what is seen as becoming contaminated, to prevent the mixing of the atmosphere, pollutants and bodies" (Cupples 2009, 211). However, it is seeking nature's "fresh" air that can "get us back to the wrong nature" (Cronon 1996). That is, one without humans in it. It is in this space that we propose CAQS, which acknowledges air pollution's material significance by doing physical air quality science, while recognising the importance of social dynamics in constructing what we do – and do not – know, and who that knowledge serves.

The recently developed critical physical geography (CPG) subdiscipline provides a useful framework to study "material landscapes, social dynamics, and knowledge politics together, as they co-constitute each other" (Lave, Biermann, and Lane 2018, 6). While CPG encompasses a diverse range of fields, methods and epistemologies, it is centred on three main intellectual tenets: hybridity, reflexivity, and power and justice (Lave, Biermann, and Lane 2018). While we use CPG's tenets as a source of inspiration for constructing CAQS, our aim is not simply to transpose CPG to the field of air quality science, but rather to be in dialogue with it. We in part make this distinction because air quality research has strong foundations in disciplines beyond geography, especially in chemistry and physics. In the following sub-sections, we take the tenets of hybridity, reflexivity, and power and justice in turn, explain their meaning and value to a focus on air pollution.

Hybridity

The tenet of hybridity recognises that the material world is tangled in political, social and economic relations and is thus co-produced by social practices and environmental processes (Whatmore 2002). Therefore one cannot rely solely on social or physical explanations for the environment (Lave et al. 2014). In the case of air pollution, it is as much the result of the intertwining of patterns of transport, consumption and city planning as it is of atmospheric chemistry, meteorology and climate change. It follows that assigning an appropriate weight to social and material explanations of patterns of air pollution becomes complicated and separating them is a potentially futile activity. For example, Clifford (2020) explains how dust is often identified as a natural source of air pollution, compared to human-made sources in urban areas such as vehicle emissions. However, this is based on a false dichotomy between nature and society: dust storms are significantly exacerbated through land-use practices that degrade soils. Therefore, approaches to understand – and ultimately improve – air quality should be "hybrid" and embrace air quality's social and material aspects, i.e. its sociomateriality (Cupples 2009).

Reflexivity

Social, political and economic relations affect the scientific gaze: the questions asked, the way research is conducted, and even research findings (King and Tadaki 2018). For air quality science this gaze amounts to a "metrological regime" (Barry 2002), whereby standardised ways of knowing the air dictate what comes to count as air pollution, and what concentrations are harmful. This requires researchers to be reflexive, to probe why certain scientific concepts and theoretical frameworks are being used, what worlds they are making visible, what relationships they are legitimising (Tadaki et al. 2015), and why we might favour some knowledge over others (Cupples 2009). The concept of reflexivity has a long history within the social sciences. Through looking at science in action to tell a warts-and-all story of how scientific facts are *constructed* (e.g. Latour 1987), it is touted as a way to express the situated – or partial – nature of scientific knowledge (e.g. Haraway 1988). Embracing reflexivity is not to say that standard scientific methods are wrong, but that they are partial and can exclude alternative ways of understanding. For example, scientific air quality risk assessments rely on assumptions about air pollution exposure risks based on "average" people that are far from representative, reduce health effects to population-level probabilistic measures and embed an approach that air pollution can be known and controlled to "acceptable" concentrations, rather than favouring a precautionary approach (Ottinger 2017).

Power and justice

Scientific knowledge production is inherently political as scientists are deeply enmeshed in a range of social relations (King and Tadaki 2018). Therefore, it has sociomaterial impacts (Law 2018). The tenet of power and justice focuses on these impacts and can be understood as an extension of reflexivity. For CAQS the choice is not between being a political activist or an apolitical detached observer, but between a range of potential political positions as "through our practices of research and our production of knowledge, we become agents of change […] our research is published and/or incorporated into environmental policy and practice" and it aligns with "particular applications and/or agendas and therefore particular politics" (Law 2018, 89–90). Air quality scientists, therefore, need to consider carefully the implications of their research by reflecting on who they are collaborating with and whose voices are – and are not – represented, who is designing the research and asking the questions, how the sources of research funding shape the research process, what science is being done and remains "undone" (e.g. Frickel et al. 2010), and who will benefit from it.

Critical air quality science

We intend for CAQS to serve as a way not only to bring the social and natural sciences together to "explode our vision of how things work, why environmental systems function the way they do … ", but also to clarify "how we […] can become more critically engaged with influencing or changing these interactions" (Urban 2018, 61). As such, the combination of tenets proposed in CAQS can help to produce an air quality science ecology whereby new forms of evidence and altered conditions by which evidences of harm can take hold are co-produced (Gabrys 2017; Stengers 2011). Figure 1 is a heuristic for how CAQS can provide a more holistic understanding of air quality. It visualises three main nodes for different areas of research: knowledge politics, material "airscapes" and social dynamics. The figure shows how material and social factors draw upon one another in their co-production, and how they both influence air quality knowledge production (Jasanoff 2004). On the lines intersecting these nodes are the combinations of tenets taken from CPG, that are best mobilised to investigate the relationships between the nodes.

While this provides a framework for guiding how undertaking CAQS should be approached, here we use it to inform our reflections on a citizen science air quality monitoring project that aimed to open up the process of knowledge production, but in ways that exposed tensions in how this materialised in practice. There are a wealth of different terminologies used to describe public participation in science (Strasser et al. 2019). We use the term "citizen science" here as it is the most widely understood term, and encompasses an extensive variety of practices. In doing so though, we neither wish to diminish important debates around how terminology can include or exclude ideas, activities, or

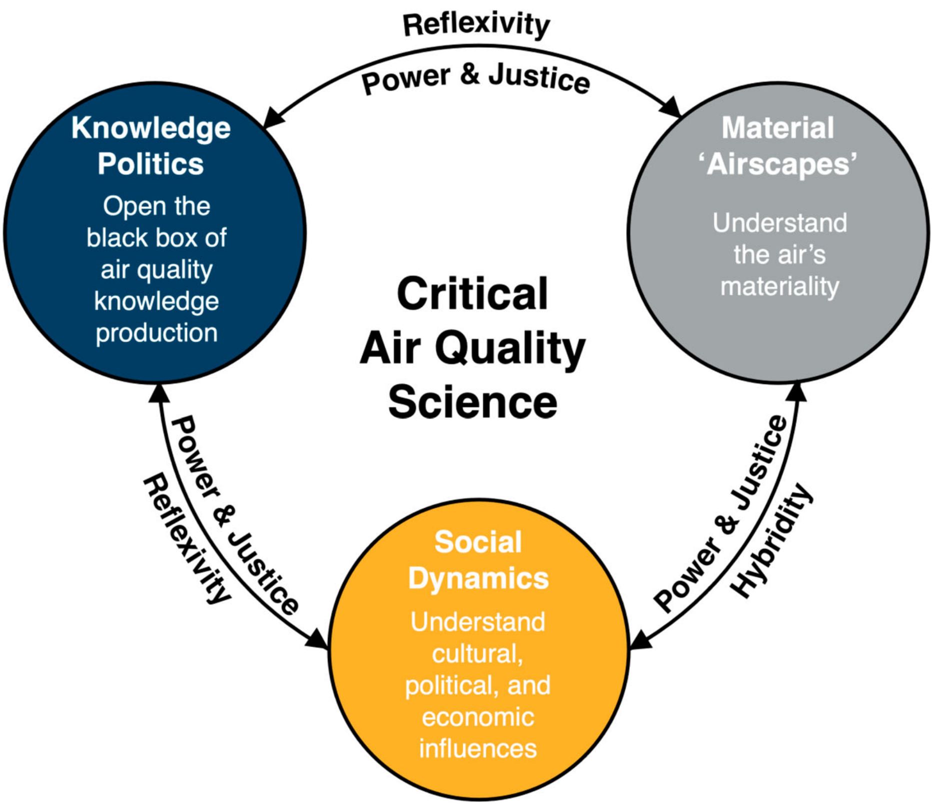

Figure 1. Critical air quality science, depicting the three main areas of research required for a holistic understanding of air quality (knowledge politics, social dynamics and material airscapes), and the tenets that can guide research methods between research areas (hybridity, reflexivity, power and justice).

people (Eitzel et al. 2017), nor distance ourselves from other terminologies, but to be in dialogue with them. In the next section, we explain more about this project and the data we draw on.

Materials and methods

Study site

Our study was situated in the Old Swan ward of Liverpool, UK, which is centred on the intersection of intra- and inter-city roads. Liverpool has been consistently ranked as one of the most deprived local authorities in England according to the Indices of Deprivation (National Statistics 2019), which include deprivation variables for the "living environment" that measure the quality of the indoor and outdoor local environment, including housing and air quality. Old Swan is a relatively disadvantaged ward within Liverpool, including for the quality of the living environment (Liverpool City Council 2019, 2021). Our study was part of the wider Neighbourhood Resilience Programme (NRP) funded by the National Institute for Health Research Collaboration for Leadership in Applied Health Research and Care in the North West Coast area of England (NIHR CLAHRC-NWC), which looked to address health inequalities in areas experiencing social and health disadvantages by tackling their root causes. Public and patient involvement in research is at the heart of NIHR CLAHRC-NWC (Ward et al. 2020). To facilitate this, the Neighbourhood Resilience Programme (NRP) was set up to support capacity building between residents, businesses, and a range of professionals working in these areas to build "system resilience", and Old Swan was one of those areas. Organised consultations and research activities with local stakeholders – including professionals working in the area and members of the public – led to the creation of the group Better Old Swan (BOS).

It soon became clear that the major arterial roads that cut through Old Swan and the effects of heavy traffic on air quality were an area of concern for BOS. Old Swan has no government air quality monitoring station and instead air quality is estimated from model simulations. This reliance on modelling was challenged by members of BOS, and has been observed in other community groups, who question models' underlying assumptions and compatibility with their "local knowledge". For example, models may fail to capture the hyperlocal air pollution that people experience as they move around urban environments, such as by cyclists in bus lanes (Yearley 1999, 2006). BOS wanted to generate its own air quality data to demonstrate their perceived problem of traffic air pollution by measuring near schools and key routes in Old Swan. CLAHRC-NWC brought the authors in to help facilitate a citizen science (CS) project to measure air pollution. To be clear, this was a pre-existing project that the authors contributed to, meaning that we did not design the project from the ground up. As such, it was not developed as an "idealised" version of CAQS but rather provides an opportunity to reflect on the approach and the challenges in practice that transdisciplinary research collaborations can entail. It also provides a perspective from a minimally-resourced and more "pragmatic" community-based project when compared to others, including some notable transdisciplinary environmental collaborations (e.g. OxAir 2021; Whatmore and Landström 2011). We refer to our collaboration with BOS in the third person as the group existed before our involvement and they were involved in other activities beyond campaigning for better air quality. However, we do use possessive references when relating to our own direct inputs (e.g. "our coding"), and areas where the process was collaborative (e.g. "we made measurements").

Data collection and analysis

In 2019, we teamed up with BOS to design and implement an air quality monitoring project using devices designed and developed by the lead author's company.[1] BOS designated responsibility to the lead author for the functioning of the air quality monitors, both due to complex operating procedures, but also BOS members' own time constraints to learn how to use them. In our case, doing undone science paradoxically required the use of a less accessible device, with a more complicated operating mechanism. However, as Froeling et al. (2021, 8) argues, “CS does not imply that projects need to use low-cost sensors, it suggests rendering monitoring practices more accessible to citizens”. We measured ultrafine particles (UFP) indoors and outdoors, an unregulated air pollutant in world-wide air quality standards that are primarily emitted by road vehicles in urban environments, and vary greatly in space and time (AQEG 2018). UFP measurements were made to investigate both the main author and BOS’s concerns about traffic air pollution from outdoors finding its way indoors. Concentrations of UFPs tend to be greater in urban areas due to a greater density of vehicles (Kumar et al. 2014), and indoor environments near busy roads have been found to experience significant concentrations of outdoor generated UFPs (Zhu et al. 2005).

We conducted 5 semi-structured interviews with members of BOS who had been involved in the air quality monitoring project to understand how they understood and aimed to use this air quality data. We used semi-structured interviews to remain close to the authors’ interests, but also to be responsive to the interests and concerns of the interviewees as they make sense of the air (Bryman 2008). While the project participants varied by sociodemographic characteristics including gender, age, profession and educational attainment, their number was not great enough to draw conclusions about the relationship between their backgrounds and how they approached the CS project (e.g. Pateman, Dyke, and West 2021). The views represented by the research participants are their individual opinions rather than the views of the wider BOS stakeholder group. The main author conducted the interviews, which were audio recorded and transcribed. On occasion, we use research participants verbatim words or phrases in prose to better express their feelings. These are not explicitly referenced but are italicised to smooth the reading experience and to clearly differentiate them from the authors’ interpretations. We completed a line-by-line open initial coding of the data followed by grouping them thematically, with themes that emerged from the data being agreed by the authors (Saldana 2009). Our coding strategy was open to emerging themes addressed by participants and the authors’ interest in the process of CS in action. This included tensions in the dynamics of knowledge production, the role of technical expertise (and scientific instruments), impacts on epistemic justice and the politics of CS. We also draw upon our experiences from interactions with BOS members through group meetings and one-to-one interactions (including installation of monitoring equipment and group data analysis), and the reflections of the authors involved in the project.

Tensions in the Better Old Swan project

In this section, we interrogate the four main tensions that emerged from our coding and data analysis. We then discuss the implications of these tensions for the practice of CAQS and reflect on how to address them when undertaking future CAQS work.

Making the doing of undone science matter in policy and practice

In this section, we focus on how citizens – through doing undone science – can challenge dominant modes of knowing the air, and in doing so we reflect on some of the tensions not just in how CS can slot into established policy processes, but also in how the policy process can make the most of CS (Irwin 2021). The success or failure of CS projects to influence policy is argued to be a function of its compatibilities with policy norms around data quality and management, organisation and governance, and alignment with current policy structures and agendas (Hecker et al. 2019). Mahajan et al. (2022) outline the science-policy-society interface for air quality CS specifically, detailing the range of different ways that citizens have attempted to translate data into policy outcomes.

The air quality data that we generated with BOS did not align with dominant ways of understanding and managing air quality in Old Swan, which focuses on measuring certain pollutants in certain spaces at certain temporal resolutions in order to meet required obligations for delivering policy objectives (Irwin 2021). The project attempted to remedy “undone science” in Old Swan in four ways. Firstly, we held a workshop with BOS group members to decide air quality measurement locations that were important to them, considering the lack of a government air quality monitoring station in the area, traffic patterns, social use of the space, and potentially negative effects of findings in chosen locations. Secondly, we decided at this workshop to measure UFPs, a key component of traffic air pollution that varies significantly in space and time and is hypothesised to be more "toxic" than larger particle sizes that are covered by air quality regulations (e.g. $PM_{2.5}$ and PM_{10}) (HEI Review Panel on Ultrafine Particles 2013). UFPs are unregulated in air quality standards worldwide, but their emissions from vehicle tailpipes are regulated, a disconnect due in part to scarce evidence of UFPs health effects, itself due to the lack of systematic measurements. This contrasts with knowledge on the health effects of legacy air pollutants such as $PM_{2.5}$ and PM_{10} that is far more established. This contradiction highlights fractured decision-making over what is worth measuring and illustrates how power relations operate to decide what is harmful. Thirdly, we made measurements of both indoor and outdoor air quality to help BOS create a narrative around outdoor air pollution coming into the indoor environment. Indoor air quality remains a comparatively undone science (Grandia 2020), receiving far less attention than outdoor air quality despite a significant portion of people spending the majority of their time indoors, and BOS participants were concerned about this. Lastly, we focused on short-term "spikes" of air pollution in Old Swan to reflect exposures at specific times of the day, rather than the longer-term averages typical of air quality regulations.

In creating these data and attempting to use them to further dialogues with policy makers and practitioners, BOS groups members lamented that *"there are no obvious ways for local projects to work with the council"*. Moreover, when one of our colleagues from the CLAHRC-NWC contacted public health officers with the results of our study the Public Health Officer claimed of our air quality data that they had *"nowhere to use this"*. The concept of a "Catch-22" was famously raised in the 1961 eponymous novel by Joseph Heller to capture a problematic situation whose solution has mutually conflicting or dependent conditions. This plagues action to remedy undone science, as in order to be seen as legitimate to decision-makers, community groups must adopt many of science's epistemic norms, values and framings to construct their claims (e.g. Ottinger 2010). This raises the question of how one can make the doing of undone science – particularly that which is locally situated and designed by those affected – matter in policy and practice.

Ottinger (2016, 99) argues that "where social movement-based citizen scientists align themselves with expert practices for the sake of scientific legitimacy, their critiques of standard scientific practices are apt to get lost". Despite focusing on an unregulated pollutant with a tight spatial and temporal resolution, we did align with expert practices by using a regulatory-compliant technique for measuring UFPs taken from vehicle emissions legislation. This acted as a "boundary bridge" to make the results more credible and difficult to dispute (Ottinger 2010). However, it is important to consider which standards are being used; using an "expert" informational structure to gain legitimacy may not translate between different groups of experts, as in the case with BOS with the difference between air quality and emissions knowledges.

Moreover, simply following regulatory practices could shut down the possibilities that citizen monitoring opens up to generate forms of evidence that match their experiences (Gabrys, Pritchard, and Barratt 2016). For BOS, we were interested in showing the effects on indoor and outdoor air quality of short-term spikes of vehicle emissions during school drop-off and pick-up. Indeed, one resident stated that the second-by-second UFP data showed *"that even one vehicle could cause a peak … "* and that *"not one of these peaks should be ignored or discounted"*.

Another way to approach this tension of making the doing of undone science matter in policy and practice is to start from a position of the purpose of the research. Our project aimed to raise awareness of air pollution with residents, galvanise new members to join BOS, and start conversations with local stakeholders to help change the sociomaterial conditions that drive air pollution in Old Swan. Gabrys, Pritchard, and Barratt (2016) mobilise the term "just good enough data" to explain the way in which data generated by citizens, alongside observations and experiences, can be used to create different forms of evidence that bring their experiences into spaces of recognition and relevance.

Rather than aiming to replicate the standard scientific and regulatory practices, which arrive at a numerical value for the air pollution concentration, citizen data can indicate patterns about when and where air pollution might be occurring, and if it is related to particular emissions sources (Gabrys, Pritchard, and Barratt 2016). These air pollution episodes in space and time may not be visible under regulatory monitoring regimes, and citizen data can be used to evidence air pollution can harm outside of the standard environmental regulations and policy, and to start a process of public conversation or collective exploration into the problem.

The concept of undone science is of particular importance for CAQS as it confronts how scientific and regulatory definitions of what counts as air pollution have neglected – and continue to neglect – the concerns of certain communities, both by constraining citizens understanding of their own environment and shaping how citizens must speak so that they are heard by those with power (Ottinger 2017). There is not a simple answer for making the doing of undone science matter in policy and practice. However, critical air quality scientists should be mindful of this dilemma as they design and carry out research, with a particular focus on "who" the research is for and its purpose.

Contesting "insiderness" and "outsiderness"

Community groups' knowledges are often framed as "non-expert", "insider", "lay" or "practical", based on their subjective beliefs and experience, or an embodied illness experience (Altman et al. 2008; Bickerstaff and Walker 2003). Conversely, "outsider" or "expert" knowledge is associated with scientific and rigorous objective reason, based on "hard" data and facts (Naples 1996). We are of the view that inside and outside are not fixed or static positions but instead shifting and permeable social locations (Naples 1996), and that CAQS should challenge assumptions about "insiderness" and "outsiderness". Our data shows how community groups and scientists can share similarities in the way they construct knowledge, and how they can transcend typical insider or outsider designations.

In addition to BOS's participants local knowledge of the area, including hotspots of air pollution, emission sources and history of urban planning, they also understood the air in Old Swan through their sensory perceptions of smell, taste, sight and hearing:

> There is a lot of noise, and the air does taste a bit funny around Prescott Road, and you can definitely smell that there's roads and vehicles around. (Participant 3)

> There [are] days when in the summer when we don't have the rain and stuff like that where if the door is left open you can actually feel the grit on the floor. You can feel it coming in, on the tables and stuff like that. (Participant 5)

Discussions also showed their knowledge of the air was through an embodied corporeal experience of coughing, choking, increased asthma and hay fever symptoms, and feeling "chesty":

> I often cough and choke when I am walking along the road […] when you're walking along and 5 or 6 buses come past together which are they are prone to do, and a couple of lorries […]. (Participant 1)

However, to limit BOS's understandings of the air to these "lay" ways of knowing would be to do them a disservice. They also demonstrated ways of knowing that are associated with traditional "scientific" knowledge including observation, quantification and linking to epidemiological research on incidences of health problems in the area. For instance, members of BOS linked their embodied experience of asthma symptoms with epidemiological research to explain incidences of asthma in the ward and family:

> Both of my children have been hospitalised with asthma when they were primary school age […] We know it is partly genetic because other members of my husband's side of the family also have asthma. However, since I moved to Liverpool there is so much more research now that I think I would be foolish to put it just down to genetics. I think it would be quite ignorant of me to do that. (Participant 2)

Moreover, BOS group members were keen on an approach that would link measured air pollution concentrations to health effects data from Alder Hey, the local Children's Hospital:

> There is a lot of people collecting data at Alder Hey for different purposes […] Maybe they could provide information on incidences of childhood respiratory diseases and link that into your data. (Participant 1)

This is an example of residents wanting to use parts of the technoscientific system to build their claims, which at least suggests they are aware of the value of some parts of the relevant expert knowledge infrastructures (e.g. Gabrys, Pritchard, and Barratt 2016; Ottinger 2010). We also do not wish to portray community members as universally having a deep inside knowledge of their conditions. Indeed, the construction of air quality as a problem recognised by "insiders" only happens if air pollution is already seen as a matter of concern (Latour 2004). In the project community members did have some prior knowledge of air pollution. However, it was not until they engaged with the Neighbourhood Resilience Programme (NRP) that they fully made sense of the effects that air quality was having on their lives. For example, in this participant's account the information provided by an NRP workshop was consequential for their awareness that air quality was an issue:

> Once we actually found out the information, I was shocked, I was overwhelmed, how it's affecting us […] once we got the information from the NHS about the elderly and the young people, and COPDs [chronic obstructive pulmonary disease], and the lung diseases. (Participant 5)

Moreover, to refer simply to insiders and outsiders to is to deny the heterogeneity of different groups. For example, BOS's make up was diverse in terms of education, life, and professional experiences and so on. The implications of assuming that citizens are non-experts poses the risk of designing methods of data collection that do not consider power dynamics within community groups, such as by only documenting the experiences of "formal" local stakeholders, only documenting the experiences of "informal" (lay) stakeholders, or mixing them in focus groups, which can alienate those who are less powerful or vocal.

The insider/outsider tension indicates that one should not underestimate the knowledge that a community might have. The construction of who is considered an "insider" and "outsider" is another manifestation of air pollution's hybridity. Managing discourses of "insiderness" and "outsiderness" is relevant for CAQS as they hold consequences for social processes that shape inequalities (Naples 1996), by serving to legitimate and "control who fe[els] entitled to speak out and who c[an] be trusted to hear" (Naples 1996, 102). Therefore, aiming to construct an environmentally just CAQS requires careful thinking to not reinforce problematic social processes, with the dichotomy between who is considered an insider/outsider as one of the most obvious examples of how particular forms of knowledge are construed and legitimated.

Traffic as both life and death

Traffic, *"the standing traffic that's just a killer"*, was frequently referred to as *"the most obvious"* source of air pollution in the neighbourhood. At the same time, residents also recognised that this *"killer"* was a significant source of life, through its associations with bringing people – and their money – into Old Swan to use its local businesses. One resident neatly encapsulated this tension when asked how this project will improve air quality in Old Swan:

> If you can get them to reduce the amount of traffic coming through the area. How they are going to do that without having a negative impact on the economy of the area, I don't know […] what Old Swan doesn't need is less people coming here as if you take any action which impacts on traffic then it will impact on people coming here and using the shops. (Participant 1)

This tension highlights how air pollution's hybridity embroils it in other societal questions and disputes: from safeguarding jobs, to how we should heat our homes and travel around towns and cities. The inextricable intertwining of air pollution's social and material components has been shown to obfuscate attempts to reduce air pollution's effects (e.g. Gramaglia 2014), and it challenged members of BOS about what form an appropriate strategy for improving air quality in the neighbourhood would take.

Given that one of BOS's main objectives was to raise awareness of air pollution in the neighbourhood to inform effective structural solutions to address its root causes, it became a point of contention for BOS about how to communicate both the purpose and results of the CS project. There was a split between a desire to frame it in a more positive and optimistic note, versus a more realist approach aimed at frightening people into action. For the latter, one BOS member noted the difference between Liverpool City Council's public health campaign for air pollution (Liverpool City Council 2018), and one warning about skin cancer from sun beds (We Are Brave 2013), bemoaning that while the skin cancer advertisements were graphic and disturbing, in the air pollution posters *"the fumes are a pretty shade of pink: are these dangers a fairy-tale?"* This difference in messaging was particularly striking when a BOS member pointed to evidence that more people died prematurely from exposure to air pollution in Liverpool than were diagnosed with skin cancer. This formed part of some BOS member's argument for an approach that should deploy scare tactics to drive action against air pollution as they argued that *"nothing else but fear or money motivates change"*. In contrast, another participant suggested that *"indignation changes nothing but your blood pressure"*, believing it is better to *"light a positive candle and communicate that to people than the […] attitude of despair and indifference and denial"*.

Confronting these tensions when reporting results is important for practising CAQS, as any research can have sociomaterial impacts and consequences. CAQS seeks to consider who benefits from the knowledge produced and who will be harmed. As BOS members alluded, the way research is reported and disseminated can lead to measurable psycho-social impacts from feeling they are living in a "risky" area (Bickerstaff 2004), inadvertently perpetuating negative stereotypes, exacerbating stigma and leading to other forms of miscrecognition (Law 2018). Compounding the stigma of those living in areas of poor air quality may influence how they are treated by further designating their environment as "dirty". This can be a factor in political decisions over who is then chosen as an appropriate recipient of certain land uses, whether that be the siting of a new industrial facility or the building of a busy road, which in turn further exacerbates air pollution concentrations (Walker 2009). The reporting and dissemination of air quality research needs to help communities achieve their goals, but should not contribute to negative stereotypes and stigma, unwittingly increasing inequalities.

To combat this, the way results are presented should locate problems in the conditions in which people live or work rather than as characteristics of individuals or groups. In doing so, you do not place the burden of pollution on those who suffer from it but allocate responsibility to the structural sources of pollution. This approach can help to reduce stigma and prevent reproducing stereotypes. For example "air pollution is high in Old Swan" could be reframed as "those living on the arterial roads of Old Swan suffer from higher traffic air pollution". However, there is still the concern that a form of realist communication might cause those with the economic means to *"run to the hills"* and leave Old Swan for the "*nice leafy suburbs*".

Changing behaviours or changing systems? Reducing air pollution vs reducing exposure

In the project, BOS members were torn between investing efforts to promote behavioural changes to reduce emissions and exposure in the short-term, and longer-term efforts to ultimately improve air quality by challenging the wider system underpinning patterns of exposure. Most air quality research projects with communities are framed with the former in mind, and are constructed as a data collecting exercise to make visible "hotspots" of air pollution, and to provide that information to residents so that they can change their behaviours to reduce their emissions and exposures (see Riley et al. 2021).

The tension here relates to how CAQS can balance short and long-term environmental justice objectives. Air pollution is damaging health in the short-term, but the current dominant focus on behavioural change does little to challenge its root causes. Moreover, research framed in behaviouralist terms might influence socioecological imaginaries by locating the responsibility for mitigating air pollution onto the individual. Instead, CAQS should work to create new imaginations that also challenge the root causes of air pollution. As imaginaries are "world making" and structure policy, values and norms, considering how they are influenced is crucial for CAQS (Gross, Buchanan, and Sané 2019).

In general, BOS members hoped that new awareness of the health effects and sources of air pollution following the project might lead to less polluting activities and reduced exposures for residents of Old Swan, as they are "*ultimately down to the individual*". This hope aligned with the narrative of a local public health campaign advocating for behavioural changes such as buying a less polluting vehicle, driving more smoothly, not idling, walking to school, parking away from schools and nurseries, and taking public transport (Liverpool City Council 2018). While this approach was seen as necessary, residents were aware that it could become a "quick fix" and insufficient for tackling the larger structural causes of air pollution. As one resident questioned, *"the solution is to keep away rather than reduce emissions?"*

To manage this dichotomous traditional way of addressing air pollution, BOS developed an animation aimed to raise awareness of air pollution in the area so that other residents could both minimise their exposure and reduce their emissions, and begin building the connections with other local stakeholders that might help change the system, and fix air quality problems at the root (Porroche-Escudero et al. 2020). BOS members' understanding of systems change included funding transport infrastructure, including cycling, electric buses, electric vehicle incentives and charging points, and unearthing old tramlines, as well as the possibility of confronting major hauliers and the firms responsible for rerouting traffic. Discussions about individual responsibility versus structural issues were also reflected in discussions between indoor and outdoor air quality: multiple BOS members said that fixing outdoor air quality should be the main focus, primarily due to the fact that they believe that individuals can make changes within their own indoor environment to improve the air quality, unlike outside where they are more reliant on structural changes.

Research that is focused on behavioural changes to reduce personal emissions and exposures is of course valuable. For example, it can mean less exposure to a vulnerable individual going to school by walking on alternative routes that are less polluted. However, we argue that an approach that focuses on this alone is akin to forever treating symptoms rather than the root cause. Moreover, it fails to recognise that many behaviour changes advocated to reduce air pollution can only take place once the right material and social structures are in place: whether that be cycling infrastructure, affordable public transport, or the time to use them (Riley et al. 2021). CAQS should consider its sociomaterial impacts and help to drive a shift in vision from individual behaviour changes to system change. This is important as visions of what air quality futures are possible structure societal understandings of agency and responsibility for poor air pollution, and who will – and will not – benefit from new air quality policies (Gross, Buchanan, and Sané 2019). However, more environmental justice research is needed in this space to theorise modes of justice that can be applied to dealing simultaneously with short- and long-term protections against air pollution.

Citizen science and critical air quality science

In this section, we focus on the broader discussions related to our case on the compatibilities between citizen science (CS) and CAQS. The analytical purchase provided by the development of CAQS has illuminated important tensions, contestations and dilemmas in CS research. For BOS that included considerations related to how air quality research was designed, carried out and communicated. To be clear, we are not saying that doing CAQS necessitates doing CS. However, it is a timely opportunity to reflect on the wider opportunities and challenges of doing them together, especially as CS methodologies are increasingly being applied to manage and better understand air quality. This includes providing low-cost air quality sensors to citizens (e.g. EEA 2019) to facilitate breakthroughs in spatiotemporal understandings of air quality (e.g. Varaden et al. 2021), and to enhance public understanding of air pollution (e.g. Mahajan et al. 2020).

CS is often heralded to provide three main benefits: *democratising science* through wider stakeholder participation in decision-making, which reduces the likelihood of marginalising communities; *improving scientific literacy* to the scientific process; and *providing new scientific breakthroughs* made possible through massive citizen participation (Strasser et al. 2019). It is easy to see the potential links between CAQS's tenets of reflexivity and power and justice, and CS's *democratising science*: both aim to open the black box of knowledge production and reconfigure it with new knowledges in the pursuit of environmental justice. However, some have questioned whether CS necessarily leads to environmental justice (e.g. Davies and Mah 2020) since alternative knowledges often remain absent (Bidwell 2009). Moreover, CS initiatives do not universally promote traditionally marginalised voices, with biases by age, sex, ethnicity and socio-economic status (Pateman, Dyke, and West 2021), something that was noticeable during the project despite our best efforts.

CS represents a wide range of practices from citizens contributing data to standard scientific practices, to being involved in all stages of the research (Haklay 2013). The type of CS enacted, who it is involving, and ultimately who the research is for, significantly affects the compatibilities between CS and CAQS. These points can be addressed when looking at the genealogy of CS, which has two distinct meanings (Cooper and Lewenstein 2016): (1) as a science that both assists the needs and concerns of citizens, and that is developed and enacted by citizens themselves (Irwin 1995) and (2) as a science where non-scientists can voluntarily contribute data to scientific projects (Bonney 1996).

These different typologies of CS affect the potential for CS and CAQS compatibility around claims of improving scientific literacy and providing new scientific breakthroughs. For example, equipping non-scientists with air quality monitors to educate them on the process of generating air quality data might help with improving non-scientist literacy. Likewise, it might help to provide new scientific breakthroughs related to higher spatiotemporal resolution understandings of air pollution. Both claims could be made about our project with BOS. However, "not even the strongest sensor with the highest-resolution open-source real-time data will be enough to magically manifest environmental justice, especially if that injustice is built on a firm foundation of inequality and oppression" (Davies and Mah 2020, 239). We do not want an approach focused just on the gathering of more, "better" data, but instead an approach that sees improving scientific literacy as a two-way street, where scientists and non-scientists learn from each other. Therefore, it was particularly important for our collaboration with BOS to focus on air quality's sociomateriality. This can also be illustrated by partnerships between citizens and local councils where citizens contribute local knowledge in participatory modelling activities to make models more robust, by ensuring that model inputs and assumptions are correct, and the priorities of research are in the right place (e.g. Yearley 2006). Beyond just improving the accuracy of scientific models, these local knowledges can also improve scientific literacy and create "data citizenships" that promote more democratic engagements with environmental data (Gabrys, Pritchard, and Barratt 2016).

There is not a one-size-fits-all CS, nor a universal CS that is suitable for CAQS. However, there are significant areas where they can coalesce or collide dependent upon the form of CS that is undertaken. A CS approach where non-scientists can voluntarily contribute data to scientific projects might be helpful in certain circumstances. Similarly, an approach that assists the needs and concerns of citizens, and that is developed and enacted by citizens themselves can also be productive. For CAQS a blend of the above would be ideal, where scientists and citizens work together to understand and reconfigure material landscapes, social dynamics and knowledge politics.

Conclusion

Air pollution is a hybrid phenomenon, known and produced through social practices *and* environmental processes. Understanding air pollution in this way requires careful consideration of how air quality science is done. This is especially true in a context which is increasingly embracing citizen science (CS), including through the deployment of low-cost sensors, and participatory monitoring and modelling practices, which challenge dominant scientific paradigms. In this paper, we combined a theoretical argument with reflections and data from interviews with citizen scientists during a collaborative air quality monitoring project. In dialogue with critical physical geography's core tenets, we proposed critical air quality science (CAQS) as a provocation to think through air quality science in a hybrid way. Using this framework, we illuminated important tensions in CS research. The first tension "Making the doing of undone science matter in policy and practice" highlighted the challenge of designing air quality research that is valuable to different sectors of society. We showed that this involves balancing alignment with expert practices and informational structures versus maintaining an element of critique by recognising and incorporating alternative knowledges. We recommended that practitioners should remember who their studies are *for* when doing CAQS. The second tension "Contesting 'Insiderness' and 'Outsiderness'" argued that inside and outside are not fixed or static positions. We reflected on how stakeholder knowledges are construed and legitimated in transdisciplinary research, and their implications for the design and reporting of air quality research. The third tension "Traffic as both life and death" illustrated the sociomaterial impacts of how research is presented. We suggested that results should be presented so that they locate problems in the conditions in which people live or work rather than as characteristics of individuals or groups, and that the perspectives of those who are affected by air pollution should be prioritised to avoid adding to their problems. The final tension "Changing behaviours or changing systems? Reducing air pollution vs reducing exposure" explored how citizen scientists can be faced with the dilemma of whether to focus on individual responsibility to minimise exposure, or structural issues aimed at reducing air pollution. We argued that this dilemma is shaped by – and shapes – potential air quality futures.

We have proposed CAQS as an attempt to reopen the conversation on how we can reconfigure air quality science to combine material and social concerns (e.g. Cupples 2009). We envisage that by simultaneously opening the black box of air quality knowledge production, understanding the air's materiality, and embracing social dynamics, CAQS can help to make sure that air quality science leads to appropriate sociomaterial interventions that do not exacerbate existing air inequalities.

Note

1. This is a small business, set up with the aim to raise awareness of indoor air quality through the development of monitoring technologies and testing services, in close interaction with academic research communities.

Acknowledgements

Thanks are due to the participating members of Better Old Swan for their hospitality, collaborative spirit, and making our citizen science experience a profoundly positive one. The views expressed in this publication are those of the author (s) and not necessarily those of the National Institute for Health Research, the Department of Health and Social Care, or NAQTS.

Disclosure statement

This work was done using equipment from the lead author's company, National Air Quality Testing Services Ltd (NAQTS). However, there is no financial benefit from this paper, it has been completed under the auspices of the lead author's PhD.

Funding

Fieldwork for this project was supported by the National Institute for Health Research Applied Research Collaboration North West Coast (NIHR ARC-NWC) (Grant Number: CLAHRC-NWC-167). The lead researcher's PhD research is sponsored by National Air Quality Testing Services Ltd (NAQTS).

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References

Altman, Rebecca Gasior, Rachel Morello-Frosch, Julia Green Brody, Ruthann Rudel, Phil Brown, and Mara Averick. 2008. "Pollution Comes Home and Gets Personal: Women's Experience of Household Chemical Exposure." *Journal of Health and Social Behavior* 49 (4): 417–435.

AQEG. 2018. "Ultrafine Particles (UFP) in the UK." https://uk-air.defra.gov.uk/assets/documents/reports/cat09/1807261113_180703_UFP_Report_FINAL_for_publication.pdf.

Barry, Andrew. 2002. "The Anti-Political Economy." *Economy and Society* 31 (2): 268–284. doi:10.1080/03085140220123162.

Bickerstaff, Karen. 2004. "Risk Perception Research: Socio-Cultural Perspectives on the Public Experience of Air Pollution." *Environment International* 30 (6): 827–840.

Bickerstaff, Karen, and Gordon Walker. 2003. "The Place(s) of Matter: Matter out of Place - Public Understandings of Air Pollution." *Progress in Human Geography* 27 (1): 45–67.

Bidwell, David. 2009. "Is Community-Based Participatory Research Postnormal Science?" *Science Technology and Human Values* 34 (6): 741–761.

Bonney, Rick. 1996. "'Citizen Science: A Lab Tradition' [in] Living Bird: For the Study and Conservation of Birds." *Living Bird: For the Study and Conservation of Birds* 15 (4): 7–15.

Brown, Phil, Brian Mayer, Stephen Zavestoski, Theo Luebke, Joshua Mandelbaum, and Sabrina McCormick. 2003. "The Health Politics of Asthma: Environmental Justice and Collective Illness Experience in the United States." *Social Science and Medicine* 57 (3): 453–464. doi:10.1016/S0277-9536(02)00375-1.

Bryman, A. 2008. *Social Research Methods*. 3rd ed. Oxford: Oxford University Press. https://books.google.co.uk/books?id=N2zQCgAAQBAJ.

Clifford, Katherine R. 2020. "Problematic Exclusions: Analysis of the Clean Air Act's Exceptional Event Rule Revisions." *Society and Natural Resources* 34 (2): 1–14.

Cooper, Caren B, and Bruce V Lewenstein. 2016. "Two Meanings of Citizen Science." In *The Rightful Place of Science: Citizen Science*, edited by Darlene Cavalier, and Eric B. Kennedy, 51–61. Tempe, AZ: Consortium for Science, Policy and Outcomes.

Cronon, William. 1996. *Uncommon Ground: Rethinking the Human Place in Nature*. New York: W.W. Norton & Company. https://books.google.co.uk/books?id=6kqjQgAACAAJ.

Cupples, Julie. 2009. "Culture, Nature and Particulate Matter - Hybrid Reframings in Air Pollution Scholarship." *Atmospheric Environment* 43 (1): 207–217.

Davies, Thom, and Alice Mah. 2020. *Toxic Truths: Environmental Justice and Citizen Science*. 1st ed. Manchester: Manchester University Press. http://library1.nida.ac.th/termpaper6/sd/2554/19755.pdf.

EEA. 2019. "Assessing Air Quality through Citizen Science." Copenhagen. https://www.eea.europa.eu/publications/assessing-air-quality-through-citizen-science/at_download/file.

Eitzel, M V, Jessica L Cappadonna, Chris Santos-Lang, Ruth Ellen Duerr, Arika Virapongse, Sarah Elizabeth West, Christopher Conrad Maximillian Kyba, et al. 2017. "Citizen Science Terminology Matters: Exploring Key Terms." *Citizen Science: Theory and Practice* 2 (1): 1. doi:10.5334/cstp.96.

Frickel, Scott, Sahra Gibbon, Jeff Howard, Joanna Kempner, Gwen Ottinger, and David J. Hess. 2010. "Undone Science: Charting Social Movement and Civil Society Challenges to Research Agenda Setting." *Science Technology and Human Values* 35 (4): 444–473.

Fricker, Miranda. 2007. *Epistemic Injustice: Power and the Ethics of Knowing. Epistemic Injustice: Power and the Ethics of Knowing*. Oxford: Oxford University Press.

Froeling, Frederique, Florence Gignac, Gerard Hoek, Roel Vermeulen, Mark Nieuwenhuijsen, Antonella Ficorilli, Bruna De Marchi, et al. 2021. "Narrative Review of Citizen Science in Environmental Epidemiology: Setting the Stage for Co-

Created Research Projects in Environmental Epidemiology." *Environment International* 152. doi:10.1016/j.envint.2021.106470.
Gabrys, Jennifer. 2017. "Citizen Sensing, Air Pollution and Fracking: From 'Caring About Your Air' to Speculative Practices of Evidencing Harm." *The Sociological Review Monographs* 65 (2): 172–192. doi:10.1177/0081176917710421.
Gabrys, Jennifer, Helen Pritchard, and Benjamin Barratt. 2016. "Just Good Enough Data: Figuring Data Citizenships Through Air Pollution Sensing and Data Stories." *Big Data & Society* July–December: 1–14.
Garnett, Emma. 2017. "Air Pollution in the Making: Multiplicity and Difference in Interdisciplinary Data Practices." *Science Technology and Human Values* 42 (5): 901–924.
Gramaglia, Christelle. 2014. "No Environmental Justice Movement in France? Controversy About Pollution in Two Southern French Industrial Towns." *Analyse Und Kritik* 36 (2): 287–313.
Grandia, Liza. 2020. "Toxic Gaslighting: On the Ins and Outs of Pollution." *Engaging Science, Technology, and Society* 6: 486–513.
Gross, Patrick Léon, Nicholas Buchanan, and Sabine Sané. 2019. "Blue Skies in the Making: Air Quality Action Plans and Urban Imaginaries in London, Hong Kong, and San Francisco." *Energy Research and Social Science* 48: 85–95.
Haklay, Muki. 2013. "Citizen Science and Volunteered Geographic Information: Overview and Typology of Participation." In *Crowdsourcing Geographic Knowledge: Volunteered Geographic Information (VGI) in Theory and Practice*, edited by Daniel Sui, Sarah Elwood, and Michael Goodchild, 105–122. Dordrecht: Springer.
Haraway, Donna. 1988. "Situated Knowledges: The Science Question in Feminism and the Privilege of Partial Perspective." *Feminist Studies* 14 (3): 575–599.
HEI Review Panel on Ultrafine Particles. 2013. *Understanding the Health Effects of Ambient Ultrafine Particles*. HEI Perspectives 3. Boston, MA: Health Effects Institute.
Hecker, Susanne, Nina Wicke, Muki Haklay, and Aletta Bonn. 2019. "How Does Policy Conceptualise Citizen Science? A Qualitative Content Analysis of International Policy Documents." *Citizen Science: Theory and Practice* 4 (1): 32. doi:10.5334/cstp.230.
Irwin, Alan. 1995. *Citizen Science: A Study of People, Expertise and Sustainable Development*. Abingdon: Routledge.
Irwin, Alan. 2021. "Citizen Science and Public Policy Making: A Thought Experiment." In *Future Directions for Citizen Science and Public Policy*, edited by Katie Cohen, and Robert Doubleday, 1–117. Cambridge: Centre for Science and Policy.
Jasanoff, Sheila. 2004. *States of Knowledge: The Co-Production of Science and the Social Order*. doi:10.4324/9780203413845.
King, Leonora, and Marc Tadaki. 2018. "A Framework for Understanding the Politics of Science (Core Tenet #2)." In *The Palgrave Handbook of Critical Physical Geography*, edited by Rebecca Lave, Christine Biermann, and Stuart N. Lane, 67–88. Cham: Springer International Publishing AG.
Kumar, Prashant, Lidia Morawska, Wolfram Birmili, Pauli Paasonen, Min Hu, Markku Kulmala, Roy M. Harrison, Leslie Norford, and Rex Britter. 2014. "Ultrafine Particles in Cities." *Environment International* 66: 1–10. doi:10.1016/j.envint.2014.01.013.
Latour, Bruno. 1987. *Science in Action: How to Follow Scientists and Engineers Through Society*. Cambridge, MA: Harvard University Press
Latour, Bruno. 2004. "Why Has Critique Run out of Steam? From Matters of Fact to Matters of Concern." *Critical Inquiry* 30: 225–248. doi:10.2307/1344358.
Lave, Rebecca, Christine Biermann, and Stuart N. Lane. 2018. "Introducing Critical Physical Geography." In *The Palgrave Handbook of Critical Physical Geography*, edited by Rebecca Lave, Christine Biermann, and Stuart N. Lane, 3–21. Cham: Springer International Publishing AG.
Lave, Rebecca, Matthew W. Wilson, Elizabeth S. Barron, Christine Biermann, Mark A. Carey, Chris S. Duvall, Leigh Johnson, et al. 2014. "Intervention: Critical Physical Geography." *Canadian Geographer* 58 (1): 1–10.
Law, Justine. 2018. "The Impacts of Doing Environmental Research (Core Tenet #3)." In *The Palgrave Handbook of Critical Physical Geography*, edited by Rebecca Lave, Christine Biermann, and Stuart N. Lane, 89–103. Cham: Springer International Publishing AG.
Liverpool City Council. 2018. "Reducing and Avoiding Air Pollution." https://letscleartheairliverpool.co.uk/how-you-can-reduce-and-avoid-air-pollution/.
Liverpool City Council. 2019. "Index of Multiple Deprivation 2019: A Liverpool Analysis. Appendix B – Liverpool Ward Analysis." Liverpool.
Liverpool City Council. 2021. "Liverpool Ward Profiles: 2021." https://liverpool.gov.uk/media/9959/old-swan.pdf.
Mahajan, Sachit, Ming-Kuang Chung, Jenny Martinez, Yris Olaya, Dirk Helbing, and Ling-Jyh Chen. 2022. "Translating Citizen-Generated Air Quality Data Into Evidence for Shaping Policy." *Humanities and Social Sciences Communications* 9 (1): 1–18. doi:10.1057/s41599-022-01135-2.
Mahajan, Sachit, Prashant Kumar, Janaina Antonino Pinto, Agnese Riccetti, Katinka Schaaf, Guillem Camprodon, Viktor Smári, Antonella Passani, and Giuseppe Forino. 2020. "A Citizen Science Approach for Enhancing Public Understanding of Air Pollution." *Sustainable Cities and Society* 52: 101800.
Naples, Nancy A. 1996. "A Feminist Revisiting of the Insider/Outsider Debate: The 'Outsider Phenomenon' in Rural Iowa." *Qualitative Sociology* 19 (1): 83–106.

National Statistics. 2019. *English Indices of Deprivation* 2019.
Ottinger, Gwen. 2010. "Buckets of Resistance: Standards and the Effectiveness of Citizen Science." *Science Technology and Human Values* 35 (2): 244–270.
Ottinger, Gwen. 2016. "Social Movement-Based Citizen Science." In *The Rightful Place of Science: Citizen Science*, edited by Darlene Cavalier, and Eric. B. Kennedy, 89–103. Tempe AZ: Consortium for Science, Policy and Outcomes.
Ottinger, Gwen. 2017. "Making Sense of Citizen Science: Stories as a Hermeneutic Resource." *Energy Research and Social Science* 31: 41–49.
Ottinger, Gwen, and Elisa Sarantschin. 2017. "Exposing Infrastructure: How Activists and Experts Connect Ambient Air Monitoring and Environmental Health." *Environmental Sociology* 3 (2): 155–165.
OxAir. 2021. "OxAir Air Quality Sensor Pilot." Oxford.
Pateman, Rachel, Alison Dyke, and Sarah West. 2021. "The Diversity of Participants in Environmental Citizen Science." *Citizen Science: Theory and Practice* 6 (1): 1–16.
Porroche-Escudero, Ana, Douglas Booker, Paula Atherton, and John Bruce. 2020. Better Old Swan Animation on Indoor Air Pollution.
Riley, Rosie, Laure de Preux, Peter Capella, Cristian Mejia, Yuya Kajikawa, and Audrey de Nazelle. 2021. "How Do We Effectively Communicate Air Pollution to Change Public Attitudes and Behaviours? A Review." *Sustainability Science* 16 (6): 2027–2047.
Saldana, J. 2009. "First Cycle Coding Methods." In *The Coding Manual for Qualitative Researchers*.
Stengers, I. 2011. *Thinking with Whitehead: A Free and Wild Creation of Concepts*. Cambridge, MA: Harvard University Press. https://books.google.co.uk/books?id=CkEtkgAACAAJ.
Strasser, Bruno J., Jérôme Baudry, Dana Mahr, Gabriela Sanchez, and Elise Tancoigne. 2019. "'Citizen Science'? Rethinking Science and Public Participation." *Science and Technology Studies* 32 (2): 52–76.
Tadaki, Marc, Gary Brierley, Mark Dickson, Richard Le Heron, and Jennifer Salmond. 2015. "Cultivating Critical Practices in Physical Geography." *Geographical Journal* 181 (2): 160–171.
Urban, Michael A. 2018. "In Defense of Crappy Landscapes (Core Tenet #1)." In *The Palgrave Handbook of Critical Physical Geography*, edited by Rebecca Lave, Christine Biermann, and Stuart N. Lane, 49–66. Cham: Springer International Publishing AG.
Varaden, Diana, Einar Leidland, Shanon Lim, and Benjamin Barratt. 2021. "'I Am an Air Quality Scientist'– Using Citizen Science to Characterise School Children's Exposure to Air Pollution." *Environmental Research* 201: 111536.
Walker, Gordon. 2009. "Beyond Distribution and Proximity: Exploring the Multiple Spatialities of Environmental Justice." *In Antipode* 41: 614–636.
Ward, Fiona, Jennie Popay, Ana Porroche-Escudero, Dorcas Akeju, Saiqa Ahmed, Jane Cloke, Koser Khan, Shaima Hassan, and Esmaeil Khedmati-Morasae. 2020. "Mainstreaming Public Involvement in a Complex Research Collaboration: A Theory-Informed Evaluation." *Health Expectations* 23: 910–918.
We Are Brave. 2013. "Liverpool City Council – The Look To Die For?" https://www.wearebrave.co/the-look-to-die-for/.
Whatmore, S. 2002. *Hybrid Geographies: Natures Cultures Spaces. Human Geography Series*. London: SAGE.
Whatmore, Sarah J., and Catharina Landström. 2011. "Flood Apprentices: An Exercise in Making Things Public." *Economy and Society* 40 (4): 582–610. doi:10.1080/03085147.2011.602540.
WHO. 2021. "WHO Global Air Quality Guidelines. Particulate Matter (PM2.5 and PM10), Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide." Geneva.
Yearley, Steven. 1999. "Computer Models and the Public's Understanding of Science: A Case-Study Analysis." *Social Studies of Science* 29: 6.
Yearley, Steven. 2006. "Bridging the Science-Policy Divide in Urban Air-Quality Management: Evaluating Ways to Make Models More Robust Through Public Engagement." *Environment and Planning C: Government and Policy* 24 (5): 701–714.
Zhu, Yifang, William C. Hinds, Margaret Krudysz, Thomas Kuhn, John Froines, and Constantinos Sioutas. 2005. "Penetration of Freeway Ultrafine Particles Into Indoor Environments." *Journal of Aerosol Science* 36 (3): 303–322. doi:10.1016/j.jaerosci.2004.09.007.