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Community-based participatory research for the study of air pollution: a review of motivations, approaches, and outcomes

Adwoa Commodore · Sacoby Wilson · Omar Muhammad · Erik Svendsen · John Pearce

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Abstract Neighborhood level air pollution represents a long-standing issue for many communities that, until recently, has been difficult to address due to the cost of equipment and lack of related expertise. Changes in available technology and subsequent increases in community-based participatory research (CBPR) have drastically improved the ability to address this issue. However, much still needs to be learned as these types of studies are expected to increase in the future. To assist, we review the literature in an effort to improve understanding of the motivations, approaches, and outcomes of air monitoring studies that incorporate CBPR and citizen science (CS) principles. We found that the primary motivations for conducting community-based air monitoring were concerns for air pollution health risks, residing near potential pollution sources, urban sprawl, living in "unmonitored" areas, and a general quest for improved air quality knowledge. Studies were mainly conducted using community led partnerships. Fixed site monitoring was primarily used, while mobile, personal, school-based, and occupational sampling approaches were less frequent. Low-cost sensors can enable thorough neighborhood level characterization; however, keeping the community involved at every step, understanding the limitations and benefits of this type of monitoring, recognizing potential areas of debate, and addressing study challenges are vital for achieving harmony between expected and observed study outcomes. Future directions include assessing currently unregulated pollutants, establishing long-term neighborhood monitoring sites, performing saturation studies, evaluating interventions, and creating CS databases.

Keywords Air quality · Citizen science · Community-based participatory research · Low-cost sensors · Exposure assessment

A. Commodore (✉) · E. Svendsen · J. Pearce
Department of Public Health Sciences, Medical University of South Carolina, 135 Cannon St., CS303, Charleston, SC 29425, USA
e-mail: commodad@musc.edu

S. Wilson
Maryland Institute for Applied Environmental Health, University of Maryland, College Park, MD, USA

O. Muhammad
Low Country Alliance for Model Communities, North Charleston, SC, USA

Introduction

It is well known that ambient air pollution is harmful to human health as research has shown associations with a broad range of health endpoints (e.g., mortality, asthma, low birth weight) (Kelly and Fussell 2015). Such research has led to increasing regulation of air pollution; however, large segments of the population continue to reside in areas with air quality concerns (Brauer et al. 2016). Historically, validation or alleviation of these concerns has proven difficult as air monitoring has traditionally been performed by governmental agencies or specialty groups due to the cost and expertise required. Realizing that such groups are unable to monitor everywhere, the air quality community has shown increasing interest in the development of community-based participatory research (CBPR) approaches to studying air pollution at the neighborhood/community scale.

In short, CBPR is a research approach that addresses concerns through the direct involvement of the community in all stages of the research process—from the initial development of the research questions to interpretation and dissemination of project results (Whitelaw et al. 2003; Minkler 2005). CBPR has the potential for tackling problems related to air pollution at the community level as—unlike traditional investigator initiated research—CBPR focuses on issues identified by the community, and, upon study completion, participants disseminate findings to the broader community to help improve conditions (Israel et al. 1998; Minkler et al. 2008b; Mayan and Daum 2016).

Historically, community-level monitoring has been difficult to conduct since ambient air quality data are obtained with expensive, complex, stationary equipment operated at the state or federal level (Chow 1995; Samet et al. 2000; Dominici et al. 2003). This left many communities with little to no option for addressing local air quality concerns. Fortunately, recent advancements in environmental monitoring technology and communications have led to the increased availability of air pollution sensors that are relatively cheap and easy-to-use resulting in rapidly evolving approaches to air pollution monitoring (Dutta et al. 2009; Devarakonda et al. 2013b; Hagler et al. 2014; Jiao et al. 2015b). Indeed, the number of community projects are growing (Dutta et al. 2009; Devarakonda et al. 2013a; Hagler et al. 2014; Jiao et al. 2015b; Duvall et al. 2016), and air quality management is interested in further exploration of this potential (NIEHS 2010; EPA 2016a).

With its capability to balance research and action, CBPR is an appropriate means for intersecting science, practice, and policy in the quest to reduce disparities in air pollution exposures (Minkler 2010). Equally important, the availability of these low-cost sensors has created new opportunities for community-based organizations to collect air pollution data using citizen science (CS): a process whereby citizens are involved in science as researchers (Kruger and Shannon 2000; Lakshminarayanan 2007; Miller-Rushing et al. 2012).

The combination of CBPR and CS for any air monitoring project creates a two-pronged opportunity for eliminating environmental disparities (Fig. 1) as there is meaningful community participation throughout the research process—including data collection, interpretation, and dissemination—and beyond, when discussions help to achieve policy changes.

However, as a newly emerging area, conducting community-level air monitoring using CBPR and CS approaches can be a difficult task (Ottinger 2010; White et al. 2012). Ambiguity in the current state of the science on community air quality monitoring, lack of awareness of the achievements by other communities, and an overall misunderstanding of data collection have been noted as concerns (Williams et al. 2014b; Williams et al. 2014c). Additionally, lack of access to information on air sensors and their performance, data quality considerations, and interpretation and communication remain considerable hurdles (Kaufman et al. 2014).

To help overcome some of these challenges, we focus the following literature review on examining community air monitoring efforts which incorporate key principles of CBPR and CS. A major goal of this type of monitoring is to combine knowledge and action to address health and environmental disparities, and some of these air monitoring campaigns may not have been published in the scientific literature (Gonzalez et al. 2011; Wilson et al. 2011). Hence, air monitoring efforts from academic journal articles, reputable web sites, and reports conducted with full community participation in various parts of the USA are discussed herein (we do briefly note in our discussion some global efforts).

To assist in our review, we divide our discussion into four main sections to address the following questions:

1. *What motivations drive communities to conduct air monitoring using CBPR and citizen science (CS) approaches and what questions are being addressed?* Here we identify community concerns that are typical drivers for community-based

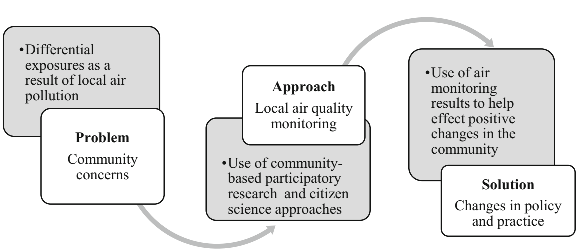

Fig. 1 Using community participation and citizen science for community-based participatory air monitoring

participatory air monitoring and discuss how various partnerships can help alleviate the concerns.

2. *Do observed outcomes of CBPR and CS air monitoring agree with expected? Which strategies are effective for achieving agreement?* In this section, we devote our time to understanding the observations and expectations of the concerned communities, while recognizing potential areas of debate and highlighting study challenges needed for achieving harmony between expected and observed study outcomes.
3. *What are the major study approaches being used and what technologies are being employed?* Here we refer to different sampling methodologies used by the reviewed air monitoring studies, and allude to emerging low-cost sensors currently available to Citizen Scientists.
4. *What are the major outcomes of CBPR and CS air monitoring and what does the future hold?* We conclude by summarizing some of the significant achievements recorded by the reviewed studies. Additionally, we offer suggestions on how CBPR and CS approaches can be steered to inform current and future research in the field of air pollution and public health in general.

Methods

Five databases were used for a literature search: EBSCOHOST platform, PubMed, SCOPUS, Science Direct, and Google Scholar. Two main search criteria were used to identify (1) community involvement and (2) air monitoring during each database search. Search terms for community participation included the following—"community based participatory research," "community engagement" "community-based air monitoring," "citizen science," "community science," "community air monitoring," "community" or "neighborhood". To detect air monitoring campaigns: "air monitoring," "air pollution," "air quality," "exposure assessment," or "air" was added to a community participation search term.

While various commendable projects have been conducted in a neighborhood or community setting, residents were not always involved in study design, data collection, or dissemination activities. We focus the major part of our review only on those studies which were in the English language, conducted in the USA, and were "community-based" as opposed to "community placed" (Minkler et al. 2008a). *Community-based* research indicates participation, research, and action by all stakeholders (i.e., community driven), while *community placed* research is the traditional "outside expert" driven research conducted in the community (i.e., investigator driven) (Minkler 2005). Criteria for inclusion were as follows: community concerns, collaboration, collective action, participatory monitoring, co-learning/capacity building, result dissemination by community members with help from other partners, and long-term commitment to sustainability (Israel et al. 2005). After reviewing over 150 abstracts, 32 studies meeting the above outlined inclusion criteria were selected. Four additional projects were identified from references in those selected studies. These 36 studies are summarized into 22 unique projects (Table 1).

The identified projects produced research that led to substantive changes to reduce pollution, lessen exposures, and address the health and environmental impacts—with the community engaged throughout (Finn and O'Fallon 2015). Additionally, some project web sites (Global Community Monitor, Community Assessment of Freeway Exposure and Health, EPA's Detroit Exposure and Aerosol Research Study, the Air Sensor Toolbox for Citizen Scientists, Trade, Health, and Environment (THE) Impact Project, Detroit Community-Academic Urban Research Center, and Transform Don't Trash NYC) provided other references for project timelines and reports.

Results and discussion

What motivations drive communities to conduct air monitoring using CBPR and CS approaches and what questions are being addressed?

Concern at various levels of the community regarding health risk attributed to air pollution was the primary motivator for CBPR air monitoring (Minkler et al. 2012). Table 1 provides the objectives, time frame, concerns, air pollutants monitored, and the accomplishments of each of the reviewed studies. Disease burdens regarding asthma, cardiovascular disease, and cancer risk were leading causes of community unease (Yip et al. 2004; Lewis et al. 2005; Brown et al. 2006; Barrett 2010; Fuller et al. 2013; Chin et al. 2014). We also discovered that broader fears of living

Table 1 Overview of air monitoring studies conducted throughout the USA with community participatory approach

Project short description	Study location	Time frame[a]	Community concerns	Objective	Main pollutants investigated	Key findings	Reference(s)
History of bucket brigade	Contra Costa County, California	1995	Fumes from a nearby petroleum refinery	To establish an independent air monitoring campaign near the oil refinery	Volatile organic compounds (VOCs) and sulfur compounds	Results revealed that there were air pollutants released from the refinery. The Environmental Protection Agency (EPA) subsequently evaluated the bucket and the monitoring results.	(Global Community Monitor 2016c)
Detroit Community-Academic Urban Research Center: community action against asthma	Detroit, Michigan	1995–present	Influence of outdoor and indoor air quality on childhood asthma	To understand and reduce the environmental triggers of asthma in children's homes and neighborhoods	Particulate matter [PM_{10}, $PM_{2.5}$ (mass and composition), and $PM_{10-2.5}$], VOCs, ozone, oxides of nitrogen (NO and NO_2), carbon monoxide (CO), black carbon (BC), elemental and organic carbon (EC, OC), and bioaerosols	Regional secondary sulfate/coal combustion, motor vehicles/combustion, refinery/oil combustion, iron–steel manufacturing/waste incineration, and automotive electroplating were all sources of air pollution—these sources were differentially distributed within the city and caused different impacts on cardiopulmonary health outcomes.	(Lantz et al. 2001; Parker et al. 2003; Yip et al. 2004; Lewis et al. 2005; Jia et al. 2008a and Jia et al. 2008b; Hammond et al. 2008; Dvonch et al. 2009; Lewis et al. 2013; Vette et al. 2012; Chin et al. 2014)
Air pollution on Harlem sidewalks	Harlem, New York City	1996	Potential health impacts of diesel vehicle emissions occurring throughout their communities	To assess street-level concentrations of air pollutants and their relationship with local diesel source emissions	$PM_{2.5}$ and elemental carbon (EC)	$PM_{2.5}$ concentrations revealed a need to consider broader regional sources of particulate matter. EC concentrations varied fourfold across sites and were mainly associated with bus and truck counts on adjacent streets and a bus depot.	(Kinney et al. 2000)
		1999			$PM_{2.5}$ and EC		(Lena et al. 2002)

Table 1 (continued)

Project short description	Study location	Time frame[a]	Community concerns	Objective	Main pollutants investigated	Key findings	Reference(s)
Air pollution in urban community heavily impacted by truck traffic	Hunts Point, New York City		Potential health effects of exposure to diesel exhaust particulates since Hunts Point is a hub in the tristate (New York, New Jersey, and Connecticut) freight transportation system.	To characterize the relationship between airborne particle concentrations and heavy-duty truck traffic		Airborne EC concentrations were elevated in Hunts Point, with truck traffic playing an important role as a determinant of spatial variations across the community.	
Global Community Monitor Projects	Kansas, Arkansas, Colorado, Ohio, Pennsylvania, New York, Wyoming, California, Alaska, Texas, Pennsylvania, New Mexico, Colorado, Delaware	2001–present	Potential impacts of air pollution in communities situated within industrial and transportation corridors	To document and understand the impacts of air pollution from industrial and transportation facilities	Particulate matter (TSP, PM_{10}, and $PM_{2.5}$), VOCs, heavy metals, elemental carbon, and polycyclic aromatic hydrocarbons (PM filter analysis)	For a majority of the GCM studies, the air quality levels were in compliance with the National Ambient Air Quality Standards (NAAQS); however, there were brief periods where the 24-h standards were violated.	(Global Community Monitor 2016a)
US EPA Environmental Monitoring for Public Access and Community Tracking (EMPACT) project: the Airbeat project	Roxbury, Massachusetts	1998–2001	Diesel truck and bus traffic, along with reports of increasing rates of asthma and other respiratory illnesses in various neighborhoods	To conduct continuous measurement of ambient air quality and develop a state-of-the-art data management and delivery system. To educate the public on the associations between air pollution and health effects	$PM_{2.5}$, ozone, and black carbon	$PM_{2.5}$ levels exceeded the 24-h limit set by the EPA (65 μg/m^3, 1997 standard) on certain days. Differences in weather caused daily and seasonal variations in ambient air quality—particularly on low wind speed days during rush hour in the Boston metropolis.	(EPA 2002b)
US EPA EMPACT project: the Paso del Norte project	Ciudad Juárez, Mexico; El Paso County, Texas; and Doña County, New Mexico	1999–2001	Rapidly increasing population growth leading to degrading environmental conditions such as air pollution	To deliver timely air quality, traffic, and weather information nationally (Texas and New Mexico) and internationally (Mexico)	Ozone, carbon monoxide, and particulate matter[b]	Environmental conditions and daily forecasts were made available to public via numerous information platforms. This led to public air quality awareness and	(EPA 2003)

Table 1 (continued)

Project short description	Study location	Time frame[a]	Community concerns	Objective	Main pollutants investigated	Key findings	Reference(s)
						reduction of exposure during unhealthy conditions.	
US EPA EMPACT project: the Northeast Ohio project	Northeast Ohio	1996–2002	Degradation of environmental quality as a result of urban sprawl	To provide local environmental and health information useful to residents and other stakeholders	Ozone, sulfur dioxide, carbon monoxide, nitrogen dioxide	A study website depicted animations and tabular presentations of current and historical data—leading to increased air quality awareness. Air quality educational programs, handbooks, and local advertisements were well received, particularly in schools where air pollution-related health problems affected many students.	(EPA 2002c)
US EPA EMPACT: Air Info Now	Tucson Arizona	1998–2002	High rates of juvenile asthma among residents of underserved regions of the Tucson metro area	To increase community access to air quality data through collection and dissemination of accurate, understandable, and timely air pollution data. To increase outreach and education programs on air quality, climate, and health effects. To create avenues for the community to address local air pollution.	Ozone	Two new monitoring sites were added to specifically target areas of concern, and the public has access to near real-time air quality information via project's page and telephone hotline.	(EPA 2002a)
US EPA Detroit Exposure and Aerosol Research Study (DEARS)	Wayne County, Michigan	2004–present	Residents in close proximity to a wide range of air pollution source categories with high emission rates, in a nonattainment area	To investigate the relationship between air pollutants from specific sources measured at a central site monitor with	PM_{10}, $PM_{2.5}$, $PM_{2.5}$ particle-bound nitrate, elemental and organic carbon (EC, OC), formaldehyde, acetaldehyde, and acrolein,	PM levels varied by neighborhood and weather patterns. Ambient concentrations of NO_2 and elemental	(Williams et al. 2009; Williams et al. 2012)

Table 1 (continued)

Project short description	Study location	Time frame[a]	Community concerns	Objective	Main pollutants investigated	Key findings	Reference(s)
				residential and personal measurements	VOCs, particle-bound SVOCs, nitrogen dioxide, sulfur dioxide, and ozone	components of $PM_{2.5}$ were associated with changes in subclinical cardiovascular function.	
Community health effects of industrial hog operations	Eastern North Carolina	2003–2005	Effects of the exposure to high-density industrial swine production on the quality of life of the neighboring communities	To investigate the relationship between exposure to pollution from industrial swine production and health outcomes	PM_{10} and semivolatile PM_{10}, together with $PM_{10–2.5}$, $PM_{2.5}$ (with subsequent filter analysis for endotoxins), and hydrogen sulfide	A framework for how community residents interpreted and responded to exposures from the industrial swine operations was developed—mainly to help them understand and manage such exposures.	(Wing et al. 2008)
Participatory testing and reporting in an environmental justice community	Worcester, Massachusetts	2004–2008	Proximity to environmentally hazardous sites and industrial facilities	To design and implement participatory testing and reporting and inform practice	$PM_{2.5}$ in indoor air, together with other environmental samples	Monitoring of neighborhood PM increased awareness of environmental health risks, particularly asthma	(Downs et al. 2010)
THE Impact project: Long Beach Alliance for Children with Asthma	Cities of Long Beach, Carson, San Pedro, Wilmington and beyond	2006–present	Poor air quality as a result of residing near transportation and industrial facilities, along with high rates of asthma and other health conditions	To identify community hot spots and measure air pollution in areas in close proximity to railway yards, freeways, and industrial facilities	Ultrafine particles	There was increased understanding of goods movement operations, and its associations with health effects. Residents partnered with the Coalition for Clean and Safe Ports to push for the Clean Trucks Program resulting in cleaner trucks, better working conditions for drivers, and funding for truck replacement.	(Truax et al. 2013)
					Ultrafine particles		(Truax et al. 2013)

Table 1 (continued)

Project short description	Study location	Time frame[a]	Community concerns	Objective	Main pollutants investigated	Key findings	Reference(s)
THE Impact project: Center for Community Action and Environmental Justice	Riverside and San Bernardino	2006–present	Impact of truck traffic, to and from warehouses, distribution centers, and a rail auto facility on local air quality	To identify community hot spots and measure air pollution in areas affected by the presence of industrial and transportation facilities		Over 700 trucks/h traveled by the homes of community members during rush hour. The disparity in exposures between the residences of local decision makers and affected communities was also evident: decision makers were less burdened by poor air quality.	
THE Impact project: Addressing Diesel Bus Traffic and Asthma in West Oakland	Oakland, California	2006–present	Exposure to diesel exhaust and traffic-related air pollutants and the high rates of asthma reported among residents	To determine the number of trucks traveling on residential streets, the amount of time trucks was idling at the Port of Oakland, and residents' air pollution exposures.	Black carbon	Approximately 6300 truck trips occurred in West Oakland daily, with about 40 trucks traveling on residential streets—an illegal move. The team also estimated that about 64 lbs./day of diesel PM emissions was generated from truck traffic and idling.	(Truax et al. 2013)
Participatory research in a Latino community	San Diego, California	2006–present	Numerous noncompliant auto body and paint shops and local air quality	To document anecdotally reported high rates of respiratory conditions in the community through the use of geographic information system mapping, surveys and air monitoring	Ultrafine particles	In 2005, over 23,000 lbs. of toxic air contaminants was released in Old Town National City, compared to 6000, 3500, and 0 lbs., from three adjacent neighborhoods.	(Minkler et al. 2010)
The Northern California Household Exposure Study	Richmond and rural Bolinas, California	2006	Effects and sources of indoor air pollution from the outdoors such as an oil refinery and truck, rail, and	To test for chemical markers of oil refinery emission in homes. To inform the community about important factors of indoor air quality	$PM_{2.5}$ and 153 analytes from quartz filters	Vanadium and nickel levels were associated with combustion from oil refining and shipping in Richmond, and nearly half of the	(Brody et al. 2009)

Table 1 (continued)

Project short description	Study location	Time frame[a]	Community concerns	Objective	Main pollutants investigated	Key findings	Reference(s)
			marine shipping industries	and the current state of science on indoor exposures and health.		homes had $PM_{2.5}$ measurements that exceeded California's annual ambient air quality standard. There were significant correlations between indoor and outdoor measurements. Sole reliance on outdoor measurements may not alleviate environmental justice concerns.	
Air quality characterization in Mission Hill	Mission Hill neighborhood, Boston, Massachusetts	2007	Sources and locations in the neighborhood with elevated air pollution	To assess spatial and temporal patterns of traffic-related air pollution	Ultrafine particles (count), $PM_{2.5}$, NO, black carbon, and PAH	Ultrafine particles had significant spatiotemporal variability, with multiple traffic factors predicted elevated levels of the pollutant. Black carbon and ultrafine particles also showed differences in diurnal patterns. Results helped local community understand local air quality and develop mitigation strategies.	(Buonocore et al. 2009)
Air pollution in vulnerable communities	North Charleston, South Carolina	2008–present	Potentially increased levels of air pollution due to additional diesel truck traffic from local port expansion activities	To assess the variability of PM in four economically distressed neighborhoods in North Charleston	$PM_{2.5}$	There was contribution to ambient PM from local air pollution sources within the North Charleston communities, although the study region is currently in attainment. Study results could serve as a baseline to	(Svendsen et al. 2014)

Table 1 (continued)

Project short description	Study location	Time frame[a]	Community concerns	Objective	Main pollutants investigated	Key findings	Reference(s)
						ascertain the impact of the increased truck and port activities on local PM concentrations.	
Community Assessment of Freeway Exposure and Health (CAFEH) air pollution studies	Somerville, Dorchester, South Boston, Chinatown and Malden communities in Boston, Massachusetts	2009–present	Exposure to highway-generated air pollution	To evaluate the association of near-highway ultrafine particles with cardiovascular health in community residents over age 40 years	Ultrafine particles, BC, CO, nitrogen oxides (NOx), particle number (PNC), particle-bound polycyclic aromatic hydrocarbons (pPAH) and $PM_{2.5}$	There was an association between individual time-activity adjusted annual average particle number concentrations and subclinical cardiovascular health biomarkers. There were also differences in exposure patterns among racial/ethnic subpopulations.	(Fuller et al. 2013; Lane et al. 2016)
Using community engagement and science to measure, educate, and communicate regional air quality	Mecklenburg, York, Gaston, Iredell, Cabarrus, Rowan, and Davidson Counties, North Carolina	2011	Lack of awareness about air pollution trends in their region	To monitor air quality in five counties currently without ambient air monitoring network and compare results to two counties with federal monitors. To increase community engagement in air quality research	NOx and ozone	Elevated levels of NOx concentrations were detected in four out of five counties, while ozone concentrations showed little variation between counties, except in two. Disseminated results increased local air quality awareness and informed stakeholders on their role in addressing air quality issues regardless of the presence or absence of ambient monitoring networks.	(Hauser et al. 2015)
Participatory air pollution assessment in a goods movement community	Philadelphia, Pennsylvania	2011–present	Effects of air pollution from diesel truck traffic traveling to and from port facility	To use CBPR to assess exposure to traffic-related air pollution	$PM_{2.5}$	Increased community awareness of mobile and point source diesel emissions through the use of photovoice and personal monitoring.	(Kondo et al. 2014)

Table 1 (continued)

Project short description	Study location	Time frame[a]	Community concerns	Objective	Main pollutants investigated	Key findings	Reference(s)
Air quality impacts of oil and gas production on nearby communities	Arkansas, Colorado, Ohio, Pennsylvania, and Wyoming	2012–2013	Emitted odors and the onset of acute symptoms experienced by residents in close proximity to unconventional oil and gas facilities (UOG)	To assess the concentrations of airborne chemicals near UOG operations. To identify production cycle steps where further monitoring may be needed	VOCs	The research team identified eight volatile compounds that exceeded ATSDR minimal risk levels or EPA Integrated Risk Information System cancer risk levels.	(Macey et al. 2014)
Chevron Richmond Refinery Fence Line and Community Air Monitoring	Richmond, California	2013–present	Impacts of emissions from refineries and industrial plants on the ambient air quality in nearby neighborhoods.	To conduct long-term continuous fence-line, and community monitoring of refinery emissions	VOCs, black carbon, PAHs, $PM_{2.5}$, ozone and sulfur dioxide	With no detections above or near the toxicity limits set by the State of California since its inception, this program is a model of formerly antagonistic stakeholders currently working together to protect clean air.	(The Richmond Community Air Monitoring Program 2016)
Mobile Device for Measuring Ambient Air Exposure, Location, and Respiratory Health	West Eugene, Oregon and Carroll County, Ohio	2013–present	Air pollution from industrial and transportation sources, increased incidence of asthma (Oregon); impact of unconventional natural gas drilling on local air quality (Ohio)	To develop a mobile device to measure personal chemical exposure, location, and respiratory function	VOCs and SVOCs	Refined scientific robustness of monitoring tools and future research directions such as seasonal variability in local air quality	(Rohlman et al. 2015)
Air monitoring in the Ironbound community	Newark, New Jersey	2015	Bordered by highways, waterways, railroads, an airport and a seaport, residents sort to understand the impact of such sources on their local air quality	To develop a specific example for conducting community-based participatory monitoring in partnership with the EPA	$PM_{2.5}$ and nitrogen dioxide	While the highest NO_2 values were recorded near major transportation corridors, $PM_{2.5}$ concentrations reflected general ambient conditions. The data can be useful for targeting sensor placement for determination of near-	(Barzyk et al. 2016)

Table 1 (continued)

Project short description	Study location	Time frame[a]	Community concerns	Objective	Main pollutants investigated	Key findings	Reference(s)
						source effects and their influence on local air quality.	
Reforming the public waste sector in New York	New York City, New York	2016	The impact of commercial waste truck traffic on local air quality, residents, neighborhoods, and the truck drivers.	To conduct air quality measurements and truck counts to inform New York's commercial waste zone planning process	$PM_{2.5}$	$PM_{2.5}$ concentrations were 2–7 times (South Bronx), up to 5 times (North Brooklyn), up to 4 times (Southwest Brooklyn), and up to 7 times (Sunset Park) higher compared to ambient levels measured by New York State Department stationary monitors. A significant amount of traffic was due to waste trucks. $PM_{2.5}$ concentrations inside waste truck cabs were up to 7 times higher than ambient levels.	(Transform Don't Trash NYC Coalition 2016)

US EPA US Environmental Protection Agency, *THE Impact project* Trade, Health, and Environment Impact Project

[a] Time frame typically begins with year of data collection and ends when entire study is complete. All studies with "–present" may be ongoing with data collection, analysis or dissemination

[b] Depending on location, all criteria pollutants from US EPA existing continuous air monitoring stations were reported

in a "toxic" environment resulted in anxiety and apprehension among community residents. In particular, concerns stemmed from proximity to potential pollution sources (e.g., mobile or point sources), as living near roadways or industry was generally perceived as "risky" (Wing et al. 2008; Brody et al. 2009; Kondo et al. 2014; Svendsen et al. 2014; Barzyk et al. 2016). Many of the studied neighborhoods were located within a few miles of major industrial and transportation corridors with point sources such as oil refineries, unconventional oil and gas facilities, concentrated animal feeding operations, and noncompliant auto body and paint shops (Wing et al. 2008; Minkler et al. 2010; Macey et al. 2014). Nonstationary sources of concern were mostly from truck, rail, and marine industries (Brody et al. 2009; Garcia et al. 2013; Truax et al. 2013; Svendsen et al. 2014). Other motivations included apprehension about future population growth and a resulting degradation of local air quality and general concerns about living in "unmonitored" areas (EPA 2002c, 2003; Buonocore et al. 2009; Hauser et al. 2015). Finally, many communities were motivated by anticipated study results such as improved air pollution knowledge, reduced air pollution risk, and reduced health burdens (Minkler et al. 2008a; Adgate et al. 2014; Cutts et al. 2015).

What questions are communities asking?

Questions that generally follow concerns are as follows: (1) Who can help? and (2) What can be done about it? To answer the first, we found that community residents formed partnerships with diverse stakeholders such as academic institutions, state and federal agencies, and, at times, the source of the concern—industry. The second question was best answered by monitoring the air, interpreting and disseminating results—with the community involved at every stage.

Additionally, when there was a focus on study outcomes that served society as a whole, and not just the community under discussion, the data obtained were relevant to broader policy and environmental needs, increased the likelihood of scientific publications, and were used by decision makers (Conrad and Hilchey 2010; McDonald-Madden et al. 2010).

Below, we present examples of how the different partnerships tackled community problems

One of the first approaches to addressing community-level air quality was the "Bucket Brigade"—a grassroots air monitoring movement pioneered by the Global Community Monitor (GCM) to help communities understand the impacts of industrial air pollution (Global Community Monitor 2016c). Faced with widespread concern about fumes from a nearby petroleum refinery, and state monitoring equipment indicating compliance with local air quality regulations, the Bucket Brigade started in 1995 in Contra Costa County, California (Global Community Monitor 2016c). The "Bucket" was designed by an engineer contracted by the community's attorney to monitor citizens' exposure to fumes. The US Environmental Protection Agency (EPA) subsequently evaluated the Bucket and monitoring results, and provided recommendations for accurate data collection (Hobson and Fishman 1998). With increasing resources and emerging technology, other projects have addressed local and regional air quality throughout the USA. This has resulted in improved air quality awareness, enhanced community capacity, and health protective policies and practices (Conrad and Hilchey 2010).

Another approach is the partnership between academic institutions and the community. A timely study to better understand a Harlem neighborhood's key concerns revealed that diesel sources contributed to variability in local air quality, and local champions were needed to ensure that research was translated to action (Kinney et al. 2000). Later in Hunts Point (a Bronx hub for a tristate transportation system), another partnership characterized the relationship between airborne particle concentrations and heavy-duty truck traffic (Lena et al. 2002). These early studies were effective demonstrations of the appropriateness of CBPR in underserved and overburdened communities, with residents as collaborators, instead of subjects.

A community-university effort with multiple academic and community partners, the Trade, Health, and Environment (THE) Impact Project, worked together to reduce the health and environmental disparities introduced by goods movement to and from the ports of Los Angeles and Long Beach (Gonzalez et al. 2011; Garcia et al. 2013). The Community Action Against Asthma, the field based project of the Detroit Community-Academic Urban Research Center, has successfully combined CBPR and air monitoring to promote health equity in the Detroit area for over two decades (Yip et al. 2004; Lewis et al. 2005; Godwin and Batterman 2007; Hammond et al. 2008; Jia et al. 2008a, b; Dvonch et al. 2009; Lewis et al. 2013; Vette et al. 2013; Chin et al. 2014). The Community Assessment of Freeway Exposure and Health (CAFEH) team partnered with Boston neighborhoods near major highways to assess traffic related air pollution (Fuller et al. 2013; Lane et al. 2016).

A third approach is through partnerships with state and federal agencies. The Environmental Monitoring for Public Access and Community Tracking (EMPACT) program created by the EPA in 1996 led to several pivotal projects in Massachusetts, Ohio, Arizona, New Mexico and Texas. EMPACT projects such as Airbeat, the Northeast Ohio project, and Air Info Now used state-of-the-art data management and delivery systems to relay air quality data to the public in near real time (Table 1). Equipped with such information, residents could make informed personal health decisions (EPA 2002a, b, c). The Paso Del Norte project, another EPA EMPACT project, utilized international collaboration between the USA and Mexico, and was a major effort by federal, state, and local agencies and educational institutions to improve regional air quality (EPA 2003). Recently, the EPA partnered with the Ironbound community in Newark to conduct community-based air monitoring using the recently developed Air Sensor Toolbox (Barzyk et al. 2016).

The partnership can be even stronger when it involves multiple academic institutions, a state or federal agency, and the community as demonstrated in North Charleston, South Carolina, by collaborators who assessed trends in local ambient particulate matter (Svendsen et al. 2014). Similarly, the Detroit Exposure and Aerosol Research Study (DEARS) has been seminal in pointing out factors that affect exposures to particulate matter and sources of local air toxics—cars, trucks, factories, and power plants (Williams et al. 2012).

Additional stakeholders capable of playing critical roles in addressing community concerns are industrial partners. Such partners can allow for better characterization of air quality near their facilities or provide funds to conduct long-term air monitoring (Macey et al. 2014; The Richmond Community Air Monitoring Program 2016). At times, with little cooperation from industry, the community can still be mobilized to collect data capable of changing future policies (Wing et al. 2008).

In our review, we found that although the blend of different backgrounds of the various partners brings diverse opinions to the field, it also helps to build credibility in areas where there is consensus (Conrad and Hilchey 2010). As such, when these stakeholders conduct research in a collaborative fashion, there are increased opportunities for improved community health (Pasick et al. 2010). Some of these opportunities include increased community directives for local decisions in siting healthcare and recreational facilities, the removal of air pollution sources, and other future planning and zoning activities. Indeed, as the EPA sums it up, it is "impossible for any single organization, institution, or sector of society, no matter how large or well established, to adequately address the environmental and/or public health problems experienced by communities" (EPA 2008). Finding more allies has the potential to increase project momentum, create environmental justice awareness, and ensure that problems are solved collectively—provided that united relationships, rather than antagonistic ones, are developed (Sherman 2004).

Do observed outcomes of CBPR and CS air monitoring agree with expected? Which strategies are effective for achieving agreement?

Many CBPR air monitoring studies are driven by residents who are concerned about air pollution in their neighborhoods based on sensory perceptions arising from visualization (e.g., smoke or haze), olfaction (e.g., foul smells), and/or gustation (i.e., taste) detections of air quality (Wakefield et al. 2001). Individuals who observe air pollution in their communities generally perceive exposures to be harmful and such perceptions will impact people's response and acceptance of CPBR study results. For example, air monitoring results, which reveal low levels of measured pollutants, may be less well received compared with results that are more confirmatory of suspicions. Ultimately, this is an issue of risk perception and risk communication that should be addressed at study onset as opposed to study completion. Studies have shown that community residents may also be uncertain of the link between air quality and health (Bickerstaff 2004; Claeson et al. 2013). However, with adequate support and training, community members actively involved in the research process can have higher confidence and better understanding of the results (Israel et al. 2001; Jones and Wells 2007).

In our review, we found that some studies had observed outcomes which agreed with expected outcomes (Kinney et al. 2000; Lena et al. 2002; Dvonch et al. 2009; Williams et al. 2012; Truax et al. 2013; Global Community Monitor 2016c). When risk assessments are possible, health impacts can be further understood. This was demonstrated in Southern California, where a formal report attributed 70% of total cancer risk to diesel emissions in communities impacted by goods movement (THE Impact Project 2009).

However, observations do not always align with expectations. For instance, several neighborhoods which partnered with the Global Community Monitor observed air quality levels that were in compliance with the National Ambient Air Quality Standards (NAAQS), although there were brief periods where the 24-h standards were violated (Global Community Monitor 2016a). While residents may have expected constant violations of the NAAQS, the data generated during the short sampling window did not support this. Further monitoring may be needed and community members most susceptible may need to be alerted during these periods of high exceedances. Real-time monitoring in the Richmond community has yet to detect any measured air pollutants above or near the limits set by the State of California, and the system has the potential to alert the community during poor air quality episodes (The Richmond Community Air Monitoring Program 2016). Others also found surprising results such as the use of illegal truck routes and the contribution of meteorology and topography to local air quality (EPA 2002b, 2003; Buonocore et al. 2009; Truax et al. 2013). Identifying effective strategies to ensure harmony between observed and expected study outcomes is desirable. In the next few sections, we pinpoint some areas of debate, highlight a few strategies used by others, and discuss challenges that may need to be addressed to achieve harmonization.

Areas of debate

Air quality studies implementing CS and CBPR methods have several areas of controversy, with particular challenges being bias, timing, and focus. Bias occurs when communities want to portray data in a way that confirms their suspicions (Brown et al. 2004), and timing becomes an issue when community members request immediate action before findings are thoroughly scrutinized (Wakefield et al. 2001). Focus is also an issue, as community organizations often desire to eliminate multiple environmental concerns, and thus, the amount of energy and resources required to attend to air pollution issues alone may be limited (Wakefield et al. 2001; Minkler 2005).

Effective strategies for achieving agreement between observed and expected outcomes

We found that the following features improved agreement between study outcomes and community expectations:

- The community identified air quality issues of concern (Israel et al. 1998).
- Community members participated fully in the design of the study, collection of the data, analyses and results interpretation (Morello-Frosch et al. 2002; Cashman et al. 2008).
- Results were disseminated by community partners, with oversight from stakeholders with the necessary expertise (Cashman et al. 2008). There was also focus on policy at times, which further indicates how CBPR can be used for action (Minkler et al. 2010).

Another step, formally documented by only one project, was an unbiased method of project evaluation which is crucial for transparency and accountability (Brown et al. 2012). On the other hand, as Minkler et al. (2010) point out, when stakeholders are not fully engaged and there is mistrust, achieving agreement can be challenging. These findings support following the CBPR framework to ensure that these types of studies are most beneficial.

Major challenges

Many challenges exist within these studies and we divide them into three central themes: (1) project organization, (2) study implementation, and (3) project completion (Fig. 2).

Project organization

Once a project scope has been defined, setting up an appropriate organizational hierarchy has been identified as a critical challenge for CBPR studies (Lantz et al. 2001; Israel et al. 2005; Israel et al. 2006; Milne et al. 2006; Vasquez et al. 2006; Conrad and Hilchey 2010; Pasick et al. 2010; Wilson et al. 2014). For air monitoring, particular challenges include the following: identifying key stakeholders, developing and sustaining meaningful relationships and decision making processes, and obtaining necessary human and material resources. Identifying stakeholders is critical and should include parties with relevant air quality expertise and community interest. Keeping communities engaged can be a challenge and positive reinforcement, mutual respect, and commitment from all parties have been shown to help address disinterest and burn-out (Whitelaw et al. 2003; Legg and Nagy 2006; Pasick et al. 2010; Truax et al. 2013). To alleviate funding

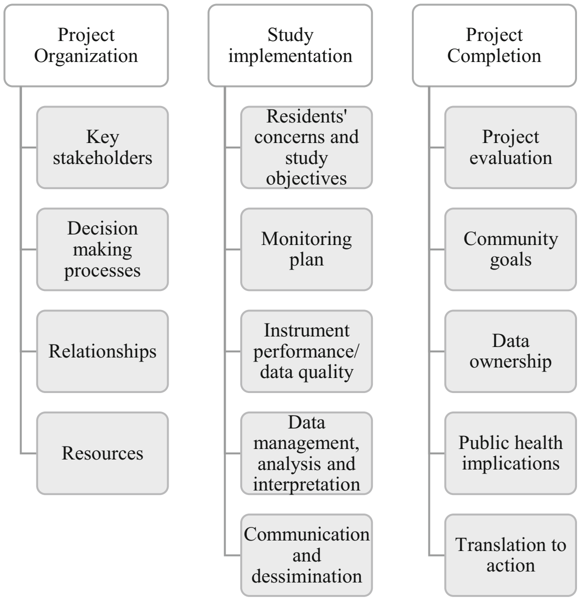

Fig. 2 Overview of some of the anticipated challenges of air pollution monitoring at the community level

concerns, potential funding agencies can tailor grant cycles to allow meaningful time for collaborators to build relationships, conduct research, disseminate results, and act on study findings (O'Fallon and Dearry 2002; Yuen et al. 2015). The EPA's Community Action for a Renewed Environment (CARE) and the Environmental Justice small grants programs are resources to help citizen scientists steer the course of their communities towards improved health and environment.

Study implementation

First, project objectives need to be clear and research questions designed appropriately prior to study commencement. Simple questions such as why and how long do we monitor must be at the forefront of all discussions since this will prevent minor concerns from becoming majors ones, leading to the eventual demise of the project (Minkler 2014). Secondly, we found effective monitoring plans included consideration of personnel, location, timing, duration, and nature of measurements (Williams et al. 2014c). Depending on the question the community aims to answer, several strategies may be needed to assess air quality, particularly in communities with different air pollution sources (Snyder et al. 2013). Employing simple monitoring, scientifically appropriate methods, and incorporating training into all aspects of these projects are important steps (Conrad and Hilchey 2010). Additionally, collaborators can focus on study outcomes that serve the greater society as this may increase the likelihood of results being published or used by decision makers (Conrad and Hilchey 2010; McDonald-Madden et al. 2010; Bonney et al. 2014).

Instrument performance/data quality Science that "stands up to careful scrutiny" must be employed throughout the project (Morello-Frosch et al. 2002; Balazs and Morello-Frosch 2013). To adequately account for quality control and address issues of data credibility, it is prudent to compare sampled data from study equipment to federal reference methods (Williams et al. 2014a; Williams et al. 2014b; Williams et al. 2015a; Williams et al. 2015b; Duvall et al. 2016). Co-locating monitoring instruments to perform intra- and inter-instrument comparison and simultaneous sampling can help address noncomparability of results (Williams et al. 2014c). There may also be challenges with data fragmentation due to equipment failure, baseline drift, power interruptions, and interferences (Whitelaw et al. 2003).

Data management, analysis, and interpretation Multiple computer programs—including open source options—are available to automatically transmit, verify, and validate data (EPA 2003). It is vital for the collaboration team to include competent statisticians and data analysts to ensure appropriate handling of technical details in data management (e.g., identifying and correcting potential problems during the process of collecting data). Data must also be appropriately stored and backed up to minimize loss, and community members can be trained to handle this properly. State-of-the-art technology now allows for unlimited data storage and retrieval; these options can be readily utilized for project success. Regular training, consistent data review, and rigorous analysis and interpretation can help maintain transparency; there are resources available to help communities maneuver this challenge (EPA 2006; Kaufman et al. 2014). Standardization and validation of procedures and techniques can provide another layer of security against this challenge (Silvertown 2009).

Communication and dissemination A final challenge at this level is the communication and dissemination of the research data so as to benefit the community (Brody et al. 2007). Residents need to be given information in a way that increases their ability to access and understand the data, and cause positive changes to occur in their daily lives (Morello-Frosch et al. 2009). It should also enhance their capacity to be more engaged in local environmental decision-making and to meaningfully use the data for pollution reduction strategies (Brown et al. 2006). Some of the reviewed studies addressed this challenge by providing multiple resources from which air quality data in real time can be easily accessed and used by community residents including websites, telephone lines, and even a flag system (EPA 2002a, b, c, 2003).

Today, technology provides numerous options for near real-time data retrieval and dissemination. A combination of air pollution sensors and telemetry allows data to be transmitted to portable devices from multiple monitoring locations (Gubbi et al. 2013; Nyhan et al. 2016). Reporting data at any time scale – from seconds to minutes is no longer daunting; the potential health implications of such instantaneous readings though, remains vague. In an attempt to interpret the often ambiguous air quality measurements obtained from low-cost sensors, the EPA has developed a messaging system to enable the public understand how short-term air quality measurements relates to local air quality and personal exposures (EPA 2016b; Mannshardt et al. 2016). Community partnerships can consider these resources to aid in data interpretation.

Project completion By far, one of the greatest challenges is the use of the data collected through the air monitoring program. It is the stage where the collaborators must address the "then what?" question. Many groups find that their data are not used in the decision-making process or even published in scientific peer-reviewed journals (Conrad and Hilchey 2011). Potential reasons for this challenge may be due to data collection concerns or difficulty in getting the data to the appropriate decision maker or journal (Conrad and Daoust 2008). Understanding which solution areas are most important for collaborators and focusing their attention on those may help circumvent this challenge (Israel et al. 2006). This may mean ongoing teamwork, educating and engaging the community, and persistent efforts in translating results into policy and practice (Israel et al. 2006).

Project evaluation The end of a monitoring campaign does not typically signal project completion or success. There needs to be some type of assessment (whether formal or informal) to ascertain whether project goals and strategies have been adhered to (Altman et al. 2008). Collaborators who incorporate CBPR and CS into their air monitoring projects can use self-developed in-house evaluations or a formal system such as the National Institutes of Environmental Health Sciences (NIEHS) Evaluation Metrics Manual to evaluate the success of projects (Brown et al. 2012; NIEHS 2012). Such evaluations help collaborators document how their projects advance science, empower communities, increase environmental literacy, and generate health protecting policies (Brown et al. 2012).

Long-term community goals This type of air quality monitoring is habitually constrained financially—often leading to uncertainty in the duration of the project and ambiguity about the end results. Major setbacks include cost of initial setup, calibrations, repairs, and regular maintenance of equipment. The few projects that surmounted this challenge have been scaled back to a fraction of their initial magnitude (e.g., Airbeat). Information on available low-cost sensor resources and community action/next steps must be updated and communicated regularly to allow for informed decisions for neighborhood level air monitoring (Graham et al. 2011; Snyder et al. 2013). Streamlined community-supported toolkits available in a number of formats must be constantly updated and improved with emerging technology and questions such as equipment end-of-life, electronic waste, and technological upgrades may need to be added (Graham et al. 2011; Newman et al. 2012; Kumar et al. 2015; Mattingly et al. 2016).

Data ownership The question of data ownership quickly arises during community-based participatory monitoring (Ottinger 2016). Particularly when it comes to the publication and use of data, it is vital for all collaborators to agree upfront on data usage, access, and purposes (Minkler 2005). If any results are shared externally, they must undergo review by all stakeholders, represent the project accurately, and honor the community (Haynes et al. 2016). Differences in opinions during such discussions are inevitable; however, they must be anchored in mutual interest and respect in order to advance scientific knowledge and improve community health (Pasick et al. 2010; Haynes et al. 2016).

Public health implications of data Adequate interpretation of the air monitoring results is needed to communicate what the results may mean to the individual, and the community as a whole (Paulos et al. 2009). We present three exposure scenarios to be anticipated: low, normal, and high. In the event of a low or normal exposure situation, the community can be assured and continue to monitor the air quality for future changes. In high-exposure situations, the following order of events may be necessary, as summarized in Fig. 3:

- Complete the data verification and validation setup for the community monitoring plan and data management to confirm the data accuracy and eliminate equipment malfunction.
- Check with the local or state air monitoring agency to verify and validate the data—a form of external check. This will also serve as a means to inform the appropriate authorities on the current air quality in the community.
- Partner with the agency to alert the community about the episode (once verified). There must be a communication plan in place (e.g., television or radio announcements, text messages, automated telephone calls, and community meetings).
- Remove or reduce the exposure, and evacuate if necessary. There must also be guidance and education for affected residents in exposure prevention. New stakeholders may need to be recruited to avoid future occurrences.

Certainly, if there is an accidental release and events are escalating, some of these steps can be quickly bypassed to ensure the safety of residents. An automated data verification and validation process, together with an updated and established alert system, can help streamline these steps and eliminate wasted time.

Translation to action CBPR and CS air monitoring results should lead to positive action that promotes health. For instance, currently in Imperial County, California, community members have partnered with researchers to establish an active community air monitoring network to provide data on local air quality and protect community health (Wilkie et al. 2016). Valuable lessons can also be gleaned from the New York Air Quality Survey, which, although not CBPR in nature, has been an important part of the city's air quality management efforts. The project has provided policy makers with data on air pollution trends, in different neighborhoods, and has documented various sources of harmful emissions (Clougherty et al. 2013; King et al. 2014). It is also critical for all collaborators to engage in policy deliberations with both short- and long-term health payoffs for the community in mind (Petersen et al. 2006; Vasquez et al. 2006).

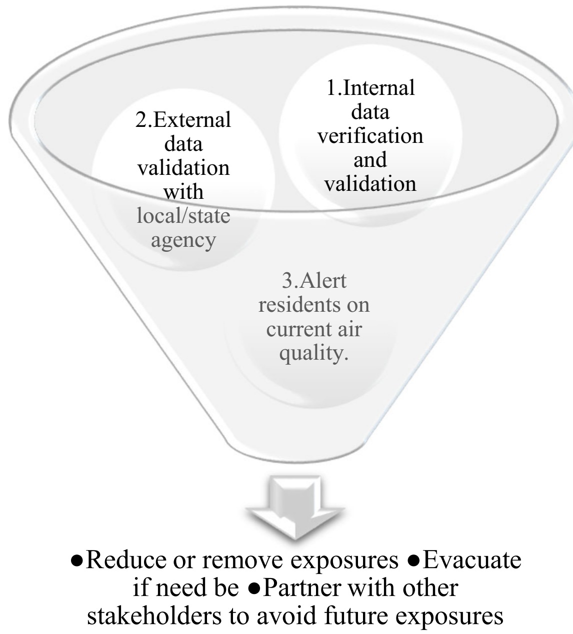

Fig. 3 An example approach to be considered during high air pollution exposure episodes in the community

What are the major study approaches being used and what technologies are being employed?

Major approaches

A variety of methods have been employed to address community air quality concerns (Fig. 4). Detailed descriptions of air sampling methods can be found in the American Industrial Hygiene Association text (DiNardi 2003) and the Air Pollution Control Technology Handbook (Schnelle and Brown 2002); herein, we briefly define these monitoring approaches. Fence-line monitoring captures emissions near the periphery of industrial facilities. Fixed site monitoring measures air quality with static instruments at a given location. Grab sampling refers to collection of an immediate air sample at a specific time, usually for analysis in a laboratory. Mobile monitoring is typically performed with equipment housed in trailers, cars, and even backpacks, which are moved around to different locations. As the names suggest, near-road assessments capture air pollution near the roadways and occupational monitoring refers

Fence-line monitoring	•N=3: Global Community Monitor projects, Richmond Community Air Monitoring Program, Wing et al. 2008
Fixed site monitoring	•N=12: Kinney et al. 2000, EPA EMPACT projects, Lena et al. 2002, Impact project, EPA DEARS, Minkler et al. 2010, Svendsen et al. 2014, Richmond Community Air Monitoring Program, CAFEH air pollution studies, Buonocore et al. 2009, CAAA
Grab sampling	•N=2: Global Community Monitor projects, Macey et al. 2014
Mobile monitoring	•N=3: CAFEH air pollution studies, Downs et al. 2010, Buonocore et al. 2009
Near-road assessments	•N=5: Impact project , CAFEH air pollution studies, Barzyk et al. 2016, Kinney et al. 2000, Transform Don't Trash NYC Coalition 2016
Occupational monitoring	•N=1: Transform Don't Trash NYC Coalition 2016
Passive sampling	•N=4: CAAA, EPA DEARS, Macey et al. 2014, Rohlman et al. 2015
Personal monitoring	•N=4: CAAA, EPA DEARS, Kondo et al. 2014, Rohlman et al. 2015
Residential monitoring	•N=7: CAAA, Impact project, CAFEH air pollution studies, EPA DEARS, Brody et al. 2009, Downs et al. 2010, Hauser et al. 2015
School monitoring	•N=1: CAAA

Fig. 4 Summary of the variety of methods used for community-based participatory air monitoring. Community Action Against Asthma (*CAAA*); EPA's Detroit Exposure and Aerosol Research Study (*EPA DEARS*); Community Assessment of Freeway Exposure and Health (*CAFEH*); EPA's Environmental Monitoring for Public Access and Community Tracking (*EPA's EMPACT*); Trade, Health, and Environment [THE] Impact Project (*Impact project*)

to monitoring air pollution in a work environment. Passive sampling employs the law of diffusion, thereby allowing air pollutants to be adsorbed unto a surface, without employing active pumping. Personal monitoring refers to air sampling conducted on individuals to capture their specific exposures, typically, within their breathing zones. Residential and school monitoring consist of any air measurements taken in close proximity on the outside or inside a home or school.

Over half of the projects surveyed used fixed site monitoring ($n = 12/22$), and this is understandable—this approach permits controlled sampling for a large array of equipment regardless of the size or weight. The equipment can also be protected from harsh weather while maintaining adequate power supply. Furthermore, it provides a broad representation of an entire neighborhood although spatial variability and time activity factors can be lost with such a method since exposures vary as people move from one microenvironment to the other. For communities who aim to identify local air pollution hot spots and assess geographical variations, using sensors that allow for mobile monitoring may be needed (Schnelle and Brown 2002).

Few studies used passive sampling ($n = 4$), grab sampling ($n = 2$), and fence-line monitoring ($n = 3$)—common methods appropriate for assessing the air quality around industrial facilities and processes. Passive and grab sampling are underutilized since such data often reflect integrated contributions of various sources over time, while fence-line sampling is often time integrated or real-time employed by one project in this review. Residential monitoring was used by seven teams—an effort which requires the support and trust of community residents, along with further time investment (Sultana and Abeyasekera 2008). For example, stimulating trust and a sense of co-ownership may help with participant retention (Downs et al. 2010). Near-road assessments ($n = 5$), often conducted to determine pollution gradients and their impacts on exposure, can provide high-quality measurements of transportation emissions and allow for better exposure modeling (Batterman 2013).

Mobile monitoring was used by three teams: one with a vehicle (Fuller et al. 2013) and the other two with participants on foot (Buonocore et al. 2009; Downs et al. 2010). These studies are typically conducted on single monitoring paths; as such, this type of linear mobile monitoring cannot thoroughly distinguish between spatial and temporal variations, and incorporating a CBPR framework further complicates matters. Communities seeking to measure the impact of traffic related air pollution in their neighborhoods can employ electric vehicles (or any mobile means) that are free from self-pollution, and evaluate both spatial and temporal variability in measurements collected with a mobile air monitoring platform (Hu et al. 2012; Yu et al. 2016). As such, this allows for new instrumentation to be used (low-cost sensors with fine time resolution), as well as changes in study design (e.g., fixed site monitoring to near-roadway or even school monitoring) to assess local air quality.

Certainly different sampling methodologies can be combined to achieve the community's aim, particularly when sampling in nontraditional environments such as workplaces and schools. For instance, private waste truck drivers installed low-cost air sensors inside their cabs to measure "indoor" $PM_{2.5}$ concentrations during their work shifts—creating an avenue to conduct mobile, personal, and occupational monitoring at the same time (Transform Don't Trash NYC coalition 2016). Another unique location is at community schools; this monitoring approach was used by the CAAA in Detroit to collect outdoor and indoor particulate matter concentrations at two community schools, effectively combining fixed site and school monitoring to help address community concerns (Yip et al. 2004). These methods can add to neighborhood level data and help explain variabilities in exposure and resulting health outcomes in special populations (Sarnat et al. 2012). Personal air monitoring was also employed by three teams in the traditional sense of active sampling with a pump. A wealth of information can be gathered from such data, although wearing a personal monitor can be burdensome. However, this method is getting easier; cellphone and other portable devices are capable of collecting data which can be easily retrieved (Willett et al. 2010; Graham et al. 2011; White et al. 2012; Castell et al. 2015). Innovative options such as passive silicone wristband samplers and the AirMapper are also available for monitoring personal exposures (O'Connell et al. 2014; Rohlman et al. 2015; EPA 2016a).

Technologies

Aside from recent developments in personal monitoring, the citizen science toolbox provides ample opportunities for individuals and neighborhoods to learn about—and use—emerging air sensor technologies (Kaufman et al. 2014) While recent improvements in airborne particulates exposure assessment has been reviewed elsewhere (Koehler and Peters 2015), several low-cost (≤$2500) single and multipollutant sensors designed for community air monitoring purposes have been evaluated by the EPA (Jiao et al. 2016) and by the South Coast Air Quality Management District (SCAQMD). Although the performance varies with sensor type (based on test of linearity: R^2) and environmental conditions, interested communities can factor in cost, study objectives, and purposes of the data to help with sensor selection. A summary of some of the evaluated sensors is provided (Table 2). Detailed summaries on recent sensor costs and performance during the laboratory and field testing are updated by the SCAQMD at http://www.aqmd.gov/aq-spec/evaluations/summary.

The EPA has also developed the citizen science air monitor (CSAM) and the sensor pod (SPOD). The former measures NO_2 and $PM_{2.5}$, together with temperature and relative humidity; the latter detects VOCs (Jiao et al. 2015a, b; Williams et al. 2015c). Other low-cost devices exist on the market and can be used to collect data when appropriate experts are consulted. A combination of methods can also be a suitable means to enhance local air pollutant characterization in complex air sheds as demonstrated with the use of the EPA's SEnsor NeTwork INtelligent Emission Locator (SENTINEL) deployed near a refinery in Philadelphia (Jiao et al. 2015a, b). At the end of the day, there must be careful selection of methods and sensors to allow community members to have the necessary knowledge and empowerment to avoid harmful exposures.

What are the major outcomes of CBPR and CS air monitoring and what does the future hold?

Main outcomes of CBPR air monitoring

A core aim for the use of CBPR is a commitment to action once the project is completed, and major achievements have been recorded with the use of CBPR and CS approaches (Minkler et al. 2008a). We briefly discuss how the action-oriented aspect of such air monitoring campaigns has resulted in significant achievements.

Lasting partnerships By far, this is the most common achievement of the majority of studies identified in this review. There appears to be strong partnerships which took years and tremendous effort to build with a majority of these still continuing to date (Table 1). Seemingly a trivial aspect of the project, partnerships have proven to be the bedrock of such air monitoring campaigns,

Table 2 US EPA evaluated low-cost sensors designed for community led air quality monitoring purposes

Name	Sensor	Communication	Evaluation results	Further information
AGT Environmental sensor	CO, CO_2, NO_2, O_3, PM_{10}	Bluetooth	O_3: $R^2 = 0.9824$, NO_2: $R^2 = 0.9972$	https://www.agtinternational.com/
Air quality egg	NO_2, CO, O_3, PM_1	Radio frequency transmitter sent to Egg base station. Base station connected via Ethernet cable to Internet	PM_1: $-0.06 < R^2 < 039$	http://airqualityegg.com/
Airbeam	$PM_{2.5}$	Bluetooth	$PM_{2.5}$: $0.66 \leq R^2 \geq <0.68$	http://aircasting.org/
Aircasting	CO, NO_2	Bluetooth	NO_2: $R^2 = 0.9846$	http://aircasting.org/
CairPol CairClip	O_3, NO_2, H_2S, CH_3SH, NH_3, VOCs	Universal serial bus (USB) or universal asynchronous receiver/transmitter (UART)	O_3: $R^2 = 0.9913$, $PM_{2.5}$: $R^2 = 0.6568$ (relative humidity [RH] > 95% and temperatures < 19.8 °C removed)	http://www.cairpol.com/index.php?lang=en
CitiSense	NO_2, NO, O_3	Bluetooth	NO_2: $R^2 = 0.9772$	http://www.citi-sense.eu
Clarity P1	$PM_{2.5}$	Wi-Fi, cellular networks, Bluetooth, UART, storage on memory card (secure digital, SD card)	NA	https://clarity.io/
Dylos DC1100	$PM_{2.5}$	UART	$PM_{2.5}$: $R^2 = 0.548$ (normalized, and RH > 95% removed)	http://www.dylosproducts.com/ornodcairqum.html
Met One 831	PM_1, $PM_{2.5}$, PM_4, and PM_{10}	USB	PM_1: $R^2 = 0.7729$ (normalized, and RH > 90% removed)	http://www.metone.com/particulate-831.php
PerkinElmer Elm	VOCs, NO, NO_2, O_3, and PM	Wi-Fi, cellular networks	O_3: $R^2 = 0.739$, NO_2: $R^2 = 0.004$, PM_{10}: $R^2 = 0.0001$	https://elm.perkinelmer.com/
RTI MicroPEM	$PM_{2.5}$	USB	$PM_{2.5}$: $R^2 = 0.72$ (RH > 94% removed)	http://www.rti.org/service-capability/engineering-technology-rd
Senspod	CO_2, CO, fine particles	Wi-Fi, storage on memory card	Model evaluated by EPA was dubbed "Sensaris Eco PM" PM_1: $R^2 = 0.3153$	http://www.sensaris.com
Shinyei PMS-SYS-1	$PM_{2.5}$	Connection to a computer via Ethernet crossover cable	$PM_{2.5}$: $R^2 = 0.152$ (RH > 95% and winds >1.7 m/s removed)	http://www.shinyei.co.jp/stc/eng/optical/main_pmmonitor.html
Speck	$PM_{2.5}$	On screen, via download, or in the cloud (designed for indoor use)	$PM_{2.5}$: $R^2 = 0.039$	https://www.specksensor.com/
SPOD	VOC	Short range XBee® (IEEE 802.15.4) network	VOCs: $R^2 = 0.7912$	https://www.epa.gov/sites/production/files/2016-04/documents/spod_fact_sheet.pdf
ToxiRAE Pro PID	VOCs	Wireless data and status transmission via an optional built-in radio frequency modem	NA	http://www.raesystems.com/products/portable-single-gas-detection/toxirae-pro-pid-voc-single-gas-detection
TZOA Research Device	Suspended particulate counts	USB, SD card, and Bluetooth	NA	http://www.tzoa.com/#homepage

Table 2 (continued)

Name	Sensor	Communication	Evaluation results	Further information
UniTec SENS-IT	CO, NO_2, O_3, C_6H_6, CH_4, SO_2, H_2S, NH_3, VOC, CO_2	UART	NO_2: $0.57 < R^2 < 0.62$, O_3: $0.72 < R^2 < 0.83$ (1 h mean), $0.33 < R^2 < 0.43$ (5 min mean), $0.63 < R^2 < 0.72$ (8 h mean); VOC: $R^2 = 0.9328$	http://www.unitec-srl.com/site/products/sens-it/
UPOD	O_3	SD card	O_3: $R^2 = 0.8775$	http://mobilesensingtechnology.com/

NA unavailable or unevaluated data

providing enriching insights and much needed support for project completion, health policy initiatives, reduction of disparities and future planning for other communities (Cashman et al. 2008; Cacari-Stone et al. 2014).

Enhanced capacity Community members increase their scientific literacy, enhance their capabilities, and recognize and expand upon community assets to address local problems (Rubin et al. 2014). With previous participation in community based air monitoring, citizen scientists understand how questions can be asked and air pollution measurements are conducted (Barzyk et al. 2016). Emerging community-focused technologies such as Geographic Information System mapping and real-time air monitoring are proving to be useful tools to help residents understand and reduce environmental disparities (Wilson et al. 2015; The Richmond Community Air Monitoring Program 2016).

Air quality awareness After using CBPR and CS approaches, some communities have a deepened knowledge of their local air quality including diurnal and nocturnal air pollution patterns and are better informed when mitigation strategies are under discussion (EPA 2002a, b, c; Wing et al. 2008; Kondo et al. 2014; Hauser et al. 2015; The Richmond Community Air Monitoring Program 2016). Others can consult daily air pollution data and forecasts to help reduce personal exposures during unhealthy conditions (EPA 2003; Louisiana Bucket Brigade 2016). In Worcester, Massachusetts, there was increased awareness of environmental health risks (Downs et al. 2010). A few communities revealed the need for, and were provided with air monitors in areas previously without ambient air monitoring networks such as in West Harlem and Tucson (EPA 2002a; Minkler et al. 2008a). Others are better informed about sensor placement for assessing air pollution sources and their influence on local air quality (Macey et al. 2014; Barzyk et al. 2016).

Health protective practices and policy Citizen science air monitoring data has been instrumental in the development of environmental justice practices and policies and improved regional air quality (EPA 2003; Minkler et al. 2008a). While most communities and their partners do not make it this far, a few groups have provided solid scientific data, e.g., evaluating associations between previously uninvestigated air pollutants and subclinical cardiovascular function (Williams et al. 2012;

Lane et al. 2016). Another project played a prominent role in implementing several specific policies and practices in Southern California such as health risk assessments, adoption of the Clean Truck Plan, the joint Clean Air Action Plan by the Ports of Long Beach and Los Angeles, and the addition of the impact of goods movement in the General Plan in the City of Commerce, California (THE Impact Project 2009; Hricko 2012).

In Harlem, New York, several achievements were recorded including the conversion of the city's bus to clean diesel, stricter air quality standards, establishment of air monitoring locations, and adoption of an environmental justice policy for the state of New York (Minkler 2010). Some neighborhoods which partnered with the Global Community Monitor advocated for green spaces, greater sustainability efforts, and air pollution emission controls and upgrades (Global Community Monitor 2016b). Undoubtedly these achievements are capable of strengthening community voices and shaping policy and practice; however, they need to be taken in context: community partnerships who apply CBPR and CS methods must be cognizant of the benefits and limitations regardless of their concerns and study outcomes.

Benefits

There are several benefits for conducting air monitoring at the neighborhood level. Firstly, it presents opportunities to maximize available resources since citizen scientists can help fill the gap created as a result of limited governmental resources (O'Rourke and Macey 2003; Conrad and Daoust 2008; Silvertown 2009; Graham et al. 2011; Newman et al. 2012; Rubin et al. 2014; Buckland-Nicks 2015). Secondly, residents can have access to informational tools that can help them understand and avoid harmful exposures (Brownson et al. 2010; Kitchin 2014; Cutts et al. 2015). Thirdly, this approach presents the opportunity to study the distribution of health outcomes among unique populations (Minkler 2005; CDC 2013). Fourthly, this fine-scale monitoring can help create a rich dataset useful for addressing public health uncertainties and quantifying risks introduced by emerging processes (Adgate et al. 2014).

Limitations

There are notable limitations for conducting community-level air monitoring. The first is differences in the technology used by regulatory agencies and citizen scientists; this prevents the use of measurements obtained from the latter group to "mandate regulatory actions" (Barzyk et al. 2016). Another shortcoming is the inability to use current low-cost sensors for source apportionment studies. A final drawback is that differences in air pollution sources, topography, meteorology, and other neighborhood specific factors may limit results extrapolation to other situations (Minkler 2005; Dominici et al. 2010).

Aside the abovementioned studies, numerous communities have undertaken community-based air monitoring efforts throughout the country. Examples include air monitoring in Garfield County, Colorado, short-term air monitoring in various communities in Minneapolis, and St. Paul by the Minnesota Pollution Control Agency. Others, such as the Delray neighborhood in Detroit, are gearing up to reduce the impact of thousands of trucks traveling through their neighborhood upon the completion of the Gordie Howe International Bridge from Canada to the USA. Many other community groups are springing up and taking charge of what happens in their neighborhoods. This is very exciting, and such efforts can be appropriately encouraged to yield desirable changes in the respective communities.

CBPR and CS outside the USA

Our discussion would be incomplete without a reflection on how these motivations, approaches, and outcomes play out in other locations around the world. In this final section, we point to differences and similarities observed in a handful of air monitoring studies that incorporated CBPR and CS principles. The predominant motivations for conducting community-based air monitoring in locations outside the USA are concerns for air pollution health risks as a result of residing near potential sources, rapid industrialization, and long range transportation of air pollutants (Hsu et al. 2013; Baklanov et al. 2016). Interestingly, the sources of air pollution are at times different from those in the USA. For example, biomass burning and Saharan dust are important air pollution sources in Africa, while rapid urbanization with associated growth in energy consumption and transportation are concerns in Asia, and industrial, transportation, and agricultural emissions sources raise concerns in Europe (Engel-Cox et al. 2013).

Although, air pollution levels are at times higher than World Health Organization guidelines, countries such as South Africa, Philippines, Thailand, and India have successfully used grab samples to ban new industrial projects in already polluted areas and have raised awareness on unhealthy air pollution levels (Global

Community Monitor 2016b). Stationary monitoring appears to be the most common sampling method, given that the nature of the typical question most citizens may be interested in answering: *what are the air pollution levels at specific locations or during specific events?* (Theunis et al. 2017). In England, the Open Air Laboratories (OPAL) project effectively used CBPR and CS principles to collect data in cost efficient ways, including a simplified citizen science methodology to detect spatial variation in nitrogenous air pollution using lichens (Tregidgo et al. 2013). Certainty, there is room for additional approaches to be utilized as this CBPR and CS principles gain popularity in other parts of the world.

The future holds much promise for combining CBPR and CS principles in international air monitoring projects. However, many challenges still abound, and may require coordinated international research infrastructure and capacity building. Some of these challenges include the following: limited air quality monitoring network and calibration capabilities, unreliable power supplies, lack of spare parts, low commitment, lack of data storage/transmittance, and the impact of politics (Engel-Cox et al. 2013). China has taken the lead in proposing a sustainability campaign to involve public interest/grass root groups to respond to haze events (Hu and Pratt 2017). Regardless of monitoring location, respecting residents' rights to information before, during, and after the project so that they can make informed decisions and reduce exposure will be a critical step.

Future directions

Citizen science can be steered to fill present gaps in air quality research such as the following:

- Measuring hazardous air pollutants (HAPs) and currently unregulated pollutants: HAPs are regulated by the EPA due to their carcinogenic and deleterious health impacts. Low-cost sensors can be employed to monitor and report these at the neighborhood and for different microenvironments. There are also unregulated air pollutants, such as ultrafine particles, black carbon, and metallic constituents in air pollution which may be worth investigating.
- Establishing neighborhood air quality monitoring sites: A station or sampling network, proven by state and federal agencies to collect valid data, presents a great opportunity for accurate air quality data to be available with limited resources at a finer scale.
- Performing saturation studies: These low-cost sensors offer the opportunity for saturation studies to occur in places where no data would have been otherwise collected.
- Evaluating interventions: Citizen scientists can assess for themselves whether an intervention was worthwhile by collecting data before and after changes occur in their communities.
- Averting catastrophic events: An established network of sensors with an alert system in the community could become a lifeline—residents can be forewarned before a major air pollution disaster overtakes the community.
- Creating a CS air quality database: An inventory of community-based air monitoring results would provide solid records for air quality data at the neighborhood level throughout the country.

Conclusion

Citizen scientists can be mobilized and educated to assess local air quality as demonstrated by several community-based air monitoring projects throughout the USA. Motivating factors for conducting such projects may be due to concerns for air pollution health risks, residing near potential sources, urban sprawl, living in unmonitored areas, and a general quest for improved knowledge. Communities have partnered with academic institutions, state and federal agencies, and even industry to assess local air quality and address these concerns. The use of fixed site monitoring was relied upon by the majority of reviewed studies; however, recent developments in single and multipollutant low-cost sensors designed for citizen scientists are expected to enable easy data collection and subsequently more thorough community characterizations. Involving the community in every step of the project, recognizing potential areas of debate, understanding benefits and limitations, and addressing study challenges were found to be important for achieving agreement between expected and observed outcomes of CBPR air monitoring. The future of air monitoring coupled with citizen science is very promising as research can be steered to fill present gaps in air quality research such as assessing hazardous and unregulated pollutants, establishing neighborhood monitoring sites, performing saturation studies, evaluating interventions, and creating CS databases.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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