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Interventions to reduce ambient air pollution and their effects on health: An abridged Cochrane systematic review

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ABSTRACT

Background: A broad range of interventions have been implemented to improve ambient air quality, and many of these have been evaluated. Yet to date no systematic review has been conducted to identify and synthesize these studies. In this systematic review, we assess the effectiveness of interventions in reducing ambient particulate matter air pollution and improving adverse health outcomes.

Methods: We searched a range of electronic databases across multiple disciplines, as well as grey literature databases, trial registries, reference lists of included studies and the contents of relevant journals, through August 2016. Eligible for inclusion were randomized and cluster randomized controlled trials, as well as several non-randomized study designs often used for evaluating air quality interventions. We included studies that evaluated interventions targeting industrial, residential, vehicular and multiple sources, with respect to their effect on mortality, morbidity and the concentrations of particulate matter (PM – including PM_{10}, $PM_{2.5}$, coarse particulate matter and combustion-related PM), as well as several criteria pollutants, including ozone, carbon monoxide, nitrogen oxides, nitrogen dioxide, nitric oxide and sulphur dioxide. We did not restrict studies based on the population, setting or comparison.

Two authors independently assessed studies for inclusion, extracted data and assessed risk of bias. We assessed risk of bias using the Graphic Appraisal Tool for Epidemiological studies (GATE) for correlation studies, as modified and employed by the UK National Institute for Health and Care Excellence. We synthesized evidence narratively, as well as graphically using harvest plots. We assessed the certainty of evidence using the Grading of Recommendations, Assessment, Development and Evaluation (GRADE) system.

Results: We included 42 studies assessing 38 unique interventions. These comprised a heterogeneous mix of interventions, including those aiming to address industrial sources (n = 5; e.g. the closure of a factory), residential sources (n = 7; e.g. coal ban), vehicular sources (n = 22; e.g. low emission zones), and multiple sources (n = 4; e.g. tailored measures that target both local traffic and industrial polluters).

Evidence for effectiveness was mixed. Most included studies observed either no significant association or an

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Abbreviations: AQG, air quality guidelines; BS, black smoke; BC, black carbon; CBA, controlled before-after study not adhering to EPOC recommended standards; CBA-EPOC, controlled before-after study adhering to EPOC recommended standards; cITS-EPOC, controlled interrupted time series study adhering to EPOC recommended standards; CO, carbon monoxide; Cochrane EPOC, Cochrane Effective Practice and Organization of Care; COPD, chronic obstructive pulmonary disease; cRCT, cluster randomized controlled trial; CVD, cardiovascular; EC, elemental carbon; GATE, Graphic Appraisal Tool for Epidemiological studies; GBD, global burden of disease study; GRADE, Grading of Recommendations, Assessment, Development and Evaluation; HEI, Health Effects institute; HIC, high-income country; ITS, interrupted time series study not adhering to EPOC recommended standards; ITS-EPOC, interrupted time series study adhering to EPOC recommended standards; LMIC, lower- and middle-income countries; NICE, National Institute for Health and Care Excellence; NO, nitric oxide; NO2, nitrogen dioxide; NOx, nitrogen oxides; NRS, non-randomized studies; O3, ozone; PICO, populations, interventions, comparisons and outcomes; PM, particulate matter; PM2.5, fine particulate matter (particles smaller than 2.5 μm in aerodynamic diameter); PM10, particulate matter (particles smaller than 10 μm in aerodynamic diameter); RAG, review advisory group; RCT, randomized controlled trial; RSP, respiratory; SO2, sulfur dioxide; UFP, ultrafine particles; WHO, world health organization

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association favoring the intervention, with little evidence that the assessed interventions might be harmful.

Conclusions: Given the heterogeneity across interventions, outcomes, and methods, it was difficult to derive overall conclusions regarding the effectiveness of interventions in terms of improved air quality or health. Some evidence suggests that interventions are associated with improvements in air quality and human health, with very little evidence suggesting interventions were harmful. The evidence base highlights the challenges related to establishing the effectiveness of specific air pollution interventions on outcomes. It also points to the need for improved study design and analysis methods, as well as more uniform evaluations. The prospective planning of evaluations and an evaluation component built into the design and implementation of interventions may also be particularly beneficial.

1. Background

Ambient air pollution is a complex mixture of particles and gases. Their concentrations and composition vary from place to place, depending on what sources are present, weather conditions, and how they mix in the atmosphere (Chow, 1995). Over the past several decades, numerous studies have documented associations between ambient air pollution and mortality and morbidity (Hoek et al., 2013; Rückerl et al., 2011; US EPA, 2009; WHO Europe, 2013). The Global Burden of Disease project has identified outdoor air pollution as one of the top five risk factors worldwide, with approximately 4 million deaths attributable to air pollution in 2016, especially in low- and middle income countries (LMICs) (Gakidou et al., 2017). Adverse health effects of ambient air pollution have been observed in vulnerable groups including children and the elderly, as well as in healthy populations (WHO Europe, 2013). It has been estimated that 92% of people worldwide live in areas where the current World Health Organization (WHO) air quality guideline (AQG) limit values for various ambient pollutants, established in 2005 (WHO Europe, 2006), are exceeded (HEI, 2019).

In order to improve air quality, a broad range of interventions have been implemented. These span national and regional regulations to local actions, and may involve either single or multiple governmental sectors (van Erp et al., 2012). They include those that influence air quality over a long period of time, e.g. the introduction of a new public transportation system, as well as those with short-term goals, e.g. the temporary closure of a road to traffic. Interventions that improve air quality may be implemented for a range of reasons, including meeting air quality standards, reducing congestion, improving traffic flow or addressing public health concerns (van Erp et al., 2012).

Air quality has improved substantially over recent years in most high-income countries (HICs), with downward trends in concentrations of several major regulatory pollutants such as particulate matter (PM: PM_{10} and $PM_{2.5}$), ozone (O_3), carbon monoxide (CO), nitrogen dioxide (NO_2), and sulphur dioxide (SO_2). However, new research has strengthened the evidence for adverse health effects of air pollution at low ambient concentrations, even those below current ambient air quality standards, supporting the case for further regulatory action (Di et al., 2017; Pinault et al., 2017). Additionally, outdoor air pollution exposures and trends differ widely across different parts of the globe, with many LMICs experiencing very high average annual concentrations and increasing trends (Cohen et al., 2017; van Donkelaar et al., 2015).

The Health Effect Institute (HEI) chain of accountability illustrates conceptually what may occur after an intervention is implemented: it must first lead to reductions in source emissions, followed by reduced ambient pollutant concentrations, reduced exposure/dose for the individual, and finally improvements in health (HEI, 2003). In considering evaluations assessing whether an intervention leads to these changes, it can be helpful to distinguish between more indirect and more direct approaches (Zigler and Dominici, 2014). Historically, many assessments of the benefits of air quality regulations have relied on more indirect approaches, which draw on concentration-response functions from existing epidemiologic studies, which are then used to predict health outcomes that might be avoided under alternative policy scenarios (Schmitt, 2016; Tonne et al., 2008). To date, however, such estimates have not been extensively validated by comparison with results of “real world” studies of regulatory programs using actual health outcome data. More direct intervention studies (often referred to as accountability studies), which refer to empirical studies assessing the effects of regulatory actions, interventions, or natural experiments (e.g. the sudden closure of a factory or a public transportation strike) on air pollution and health, have emerged to fulfill that role (van Erp et al., 2012). Intervention studies typically compare air quality and/or population health before and after implementation of a policy, although they often defy a clear study design classification. Intervention studies are appealing since they are the closest epidemiologic equivalent to controlled experimental studies in the field of air pollution health research, and thus may provide evidence for causal relationships.

Research generally shows that the introduction of multiple interventions over long periods of time is associated with improved air quality and health (Boogaard et al., 2013; Correia et al., 2013; Dominici et al., 2007; Gauderman et al., 2015; Gilliland et al., 2017; Pope et al., 2009; Schindler et al., 2009). The extent to which individual interventions contribute to improved outcomes is less clear. Recent literature reviews have summarized the evidence (Bell et al., 2011; Boogaard et al., 2017; Henneman et al., 2017; Henschel et al., 2012; Rich, 2017). To date, however, no systematic review has been performed with broad, systematic literature searches and standardized, transparent and rigorous methods for selecting, appraising and synthesizing the evidence base.

2. Objectives

To assess the effectiveness of interventions in reducing ambient particulate matter air pollution and improving adverse health outcomes in humans.

3. Methods

The methods for this systematic review are described in detail in a published protocol (Burns et al., 2014) and summarized below. To ensure that the review would appropriately inform policy, protocol development was informed by a Review Advisory Group (RAG), comprising air pollution and health experts as well as potential end-users of the review from a wide range of countries and contexts.

In conducting the Cochrane systematic review, we divided the included studies into main studies that contributed intervention effects to the evidence synthesis and supporting studies that contributed only descriptive data to the review results. Supporting studies included those conducting non-analytical descriptive comparisons and those which applied study designs less suitable for assessing intervention effectiveness, e.g. uncontrolled before-after studies. This abridged version of our Cochrane systematic review focuses on the synthesis of our ‘main studies’ (i.e. studies utilizing research designs considered to be more reliable for assessing causality). For an additional descriptive synthesis of supporting studies please see the full review (Burns et al., 2019). Otherwise, the methods, results and interpretations reported here reflect those of the full review; they have been abridged to reach a broader audience working on air pollution research and policy.

3.1. Inclusion criteria

3.1.1. Types of studies

Accountability studies in the field of air pollution are generally not randomized because of ethical, practical and feasibility reasons (Craig et al., 2017; Higgins et al., 2012). Thus non-randomized studies (NRS) of interventions comprise the main source of evidence to assess the effectiveness of ambient air quality interventions (Bell et al., 2011; Boogaard et al., 2017; Henneman et al., 2017; Henschel et al., 2012; Rich, 2017). The following study designs were therefore eligible for inclusion:

- Individually (RCTs) and cluster (cRCTs) randomized trials
- Controlled before-after studies adhering to standards recommended by the Cochrane Effective Practice and Organization of Care (EPOC) Group (CBA-EPOC) – assessed pre- and post-intervention data for at least two intervention sites and two control sites (Cochrane EPOC, 2017);
- Interrupted time series studies adhering to EPOC standards (ITS-EPOC) – with at least three data points before and after a clearly defined intervention (in terms of content and timing) (Cochrane EPOC, 2017);
- Controlled ITS studies (cITS-EPOC) – applied an ITS-EPOC study design, and also included data from one or more control sites;
- Controlled before-after studies not adhering to EPOC standards (CBA) – assessed pre- and post-intervention data at fewer than two intervention and/or control sites;
- Interrupted time series studies not adhering to EPOC standards (ITS) – with fewer than three data points before and after a clearly defined intervention (in terms of content and timing).

3.1.2. Types of populations, interventions, comparisons and outcomes

Overall, the inclusion criteria with regard to the populations, interventions, comparisons and outcomes (PICO) of interest were broad; these are summarized in Table 1. Notably, we defined four broad intervention categories a priori, including interventions targeting industrial, residential, vehicular and multiple sources.

3.2. Search methods for identification of studies

We performed searches within multiple general, specialist and regional databases, including CENTRAL, Cochrane Public Health Group Specialised Register, MEDLINE, EMBASE, PsycINFO, Scopus, Science Citation Index, Social Science Citation Index, Greenfile, the Global Health Library regional indexes: AIM (AFRO), LILACS (AMRO/PAHO), IMEMR (EMRO), IMSEAR (SEARO), WPRIM (WPRO), and WHOLIS. Sources for grey literature, other unpublished or in press articles

Table 1
PICO- related inclusion criteria applied within the review.

Population	No restrictions. For health outcomes, eligible populations could be any group of individuals, exposed to an intervention of interest (e.g. all residents living in a city center where a low emission zone is implemented). Chamber studies or studies simulating the real-word conditions in a laboratory setting were not considered. For air quality outcomes, eligible studies measured pollutant concentrations of relevance to defined human populations (e.g. air quality measured at multiple monitoring sites across a city where a low emission zone is implemented).
Intervention category	● **Industrial interventions** - Examples: emission standards and regulations for power plants and other industrial sources, fuel changes. ● **Residential interventions** - Examples: stove exchange programs, banning the sale and use of coal ● **Vehicular interventions** - Examples: low emission zones, vehicle charging schemes, public transportation expansion; fuel and technology changes ● **Multiple interventions** - Examples: coordinated policies such as the European National Emission Ceilings Directive, measures during international sporting events, such as the 2008 Beijing Olympic Games.
Comparison	No restrictions
Outcome	**Primary outcomes** ● Mortality from the following causes: - all-cause - cardiovascular - respiratory ● Concentrations* of particulate matter and related measures. These served as primary outcomes due to their important role in monitoring globally, as well as their well-documented association with adverse health outcomes: - PM_{10} - $PM_{2.5}$ - Coarse PM - Soot - Black carbon (BC) - Black smoke (BS) - Elemental carbon (EC) **Secondary outcomes** ● Respiratory and cardiovascular effects: - Lung function - Respiratory events, including symptoms - Respiratory hospital admissions - Cardiovascular events, including symptoms - Cardiovascular hospital admissions ● Concentrations* of: - CO - SO_2 - NO_x - O_3 - Ultrafine particles (UFP) - Personal PM exposure *Pollutant concentrations had to be real-world measurements for studies to be included; modeling studies were not considered

included HMIC, WHO ICTRP, ClinicalTrials.gov, IDEAS, JOLIS, 3ie impact, and PubMed ahead of press. The final search date for all databases was 31 August 2016.

The search strategy was designed in Medline, and then adapted for all other databases; all search syntax histories can be found in the full review.

In addition to the electronic search, we hand-searched the references of included studies, and the tables of contents of Environmental Health Perspectives and Atmospheric Environment for the 12 months preceding the last search date. Searches were conducted in English, but we endeavored not to exclude any studies on the basis of language.

3.3. Data collection and analysis

3.3.1. Selection of studies

Following removal of duplicate studies, we performed a multistage screening process. In the first stage, one author screened all titles, removing those clearly not relevant (e.g. animal studies, chamber studies, letters to the editor). In the second stage, two authors (JB, HB, SP, LP, AR, AvE, ER) independently screened all remaining titles and abstracts. In the final screening stage, two authors independently examined the full text of all potentially relevant studies, assessing each against a checklist of inclusion criteria. At each stage, disagreements were resolved through discussion, and a third author was consulted where necessary.

3.3.2. Data extraction and management

We developed and piloted a data extraction form based on a standardized template provided by Cochrane Public Health, which allowed us to capture information on the interventions, outcomes, study designs and analyses, context and implementation of included studies. For all included studies, two authors (JB, HB, SP, LP, AR, ER) independently extracted data. Inconsistencies or disagreements were resolved through discussion, and a third author was consulted where necessary.

3.3.3. Assessment of the internal and external validity of individual studies

To assess the internal and external validity of included studies, we used the Graphic Appraisal Tool for Epidemiological studies (GATE) for correlation studies, as modified and employed by the Centre for Public Health Excellence at the UK National Institute for Health and Care Excellence (NICE). This modified GATE tool is well suited to the assessment of the internal and external validity of non-randomized intervention studies in public health, especially where studies differ substantially from traditional clinical trials (Jackson et al., 2006; NICE, 2012). It performed well compared to five other risk of bias or quality appraisal tools in a recent methodological study (Voss and Rehfuess, 2013). The GATE appraisal checklist is divided into five sections consisting of 18 criteria, and allows for a systematic assessment of aspects related to the external validity (section 1: population) and internal validity or risk of bias (sections 2–4: method of selection of exposure or comparison group; outcomes; analyses) of a study. A fifth section then allows the review authors to give each study an overall rating for both external and internal validity. Possible ratings include (+ +), (+) or (−), which are defined as follows:

> (+ +) indicates that all or most of the checklist criteria have been fulfilled; and where they have not been fulfilled the conclusions are very unlikely to alter;
> (+) indicates that some of the checklist criteria have been fulfilled; where they have not been fulfilled, or are not adequately described, the conclusions are unlikely to alter;
> (−) indicates that few or no checklist criteria have been fulfilled and the conclusions are likely or very likely to alter.

After calibrating use of the tool within the team, two authors (JB, HB, SP, LP, AR, ER) independently appraised all included studies. Disagreements were resolved through discussion, and a third author was consulted where necessary. Where studies applied different study design and analysis methods to assess health and air quality outcomes, we conducted two separate assessments.

3.3.4. Data synthesis

As the evidence proved too heterogeneous to conduct meta-analyses, in line with the review protocol, we conducted both a narrative synthesis and a graphical synthesis using harvest plots. Harvest plots have been shown to be an effective, clear and transparent way to summarize evidence of effectiveness for complex interventions (Ogilvie et al., 2008; Turley et al., 2013). We created four separate harvest plots, one for each of the four intervention categories. The rows represent the different outcomes. The columns indicate the direction of effect – effect favors control, unclear effect due to lack of statistical significance, effect favors intervention. A bar illustrates the effect direction for a single study reporting that particular outcome. Where multiple studies assessed the same outcome for a given intervention, we included the effect estimate from the study with the lowest risk of bias; where the same risk of bias rating was given, we chose the effect estimate from the study with the most recent follow-up. The risk of bias of the study is illustrated by the height of the bar. We created harvest plots in Microsoft PowerPoint.

3.3.5. Certainty of the body of evidence

In addition to assessing the quality of an individual study (for which we used the modified GATE tool), we assessed the certainty of the body of evidence using the Grading of Recommendations, Assessment, Development and Evaluation (GRADE) system (Guyatt et al., 2008).

We applied GRADE to the body of evidence comprising each intervention category and primary outcomes, e.g. all studies assessing interventions that target industrial sources on all-cause mortality. We created a ‘Summary of findings’ table for each of the four intervention categories. The initial GRADE assessment was undertaken by one author (JB), and was then discussed in detail and finalized with a second author (ER).

4. Results

4.1. Description of studies

4.1.1. Results of the search

The results of the selection of studies are shown in Fig. 1. From a total of 28,219 unique records, 292 full texts were deemed potentially relevant, and 119 met the a priori eligibility criteria and were included in the review. Reasons for exclusion at the full text screening stage are documented in Fig. 1; at the stage of full-text screening, most studies (n = 100; 58%) were excluded due to their study design.

Of the 119 studies that met the full inclusion criteria, 42 were included as main studies. The characteristics of these 42 studies are described in this review.

4.1.2. Included studies

The characteristics of each of the 42 included studies are summarized in the text below and described in detail in Table 2.

4.1.3. Setting

Included studies assessed interventions from 19 different countries (Fig. 2). Although there was a wide geographical distribution of included studies, using the Global Burden of Disease (GBD) super-region classification (Gakidou et al., 2017), most of the assessed interventions were from HICs (n = 30) (Allen et al., 2009; Atkinson et al., 2009; Bel and Rosell, 2013; Boogaard et al., 2012; Burr et al., 2004; Cowie et al., 2012; Deschênes et al., 2012; Dijkema et al., 2008; Dockery et al., 2013; Dolislager, 1997; Fensterer et al., 2014; Gallego et al., 2013; Giovanis, 2014; Hasunuma et al., 2014; Johnston et al., 2013; Kim and Shon,

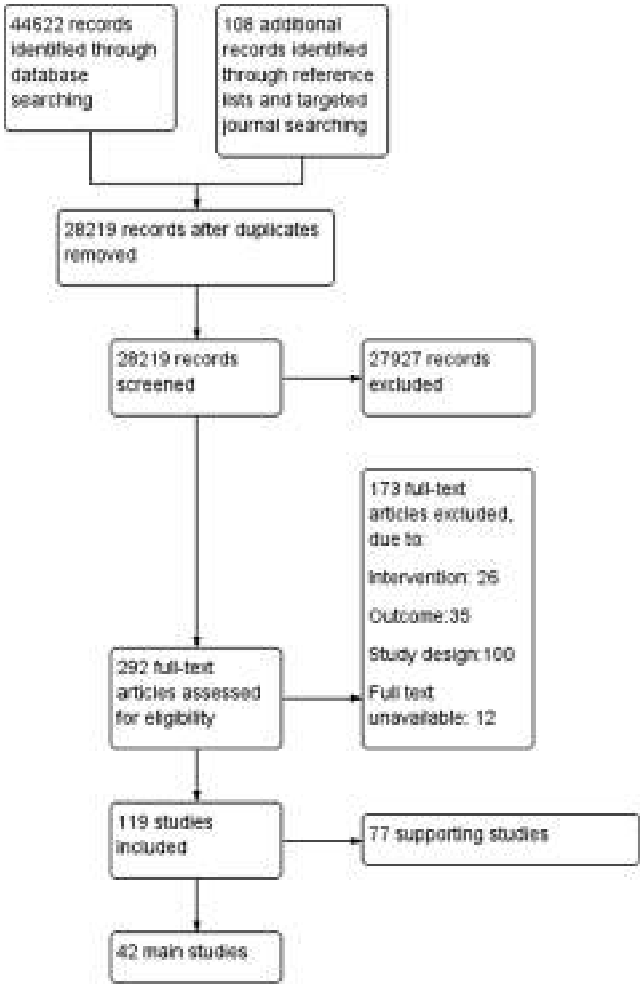


Fig. 1. Study flow diagram.

2011; Morfeld et al., 2014; Mullins and Bharadwaj, 2014; Peel et al., 2010; Pope et al., 2007; Ruprecht and Invernizzi, 2009; Saaroni et al., 2010; Sajjadi et al., 2012; Titos et al., 2015; Yap and Garcia, 2015; Yorifuji et al., 2016; Zigler et al., 2016) Interventions in LMICs were also included, but most of the non-HIC super-regions were poorly represented; three interventions were assessed in the Southeast Asia, East Asia and Oceania region (Li et al., 2011; Tanaka, 2015; Viard and Fu, 2015), two interventions in the Latin America and the Caribbean region (Carrillo et al., 2016; Davis, 2008), one intervention in Central Europe, Eastern Europe and Central Asia (Titos et al., 2015), one intervention in the North Africa and the Middle East region (El-Zein et al., 2007) and one intervention in the South Asia region (Aung et al., 2016). Notably, we did not identify any interventions in the sub-Saharan Africa region. Most interventions (n = 29) were implemented in an urban setting, while two studies examined interventions in rural settings and a further seven examined interventions in mixed urban/rural settings.

4.1.4. Population

This review comprises both studies that measure air quality only and studies that measure health, either alone or in combination with air quality. In studies assessing air quality only, most used routinely monitored data collected for regulatory purposes, although some collected data from study-specific pollutant monitors. In studies assessing only health or health and air quality combined, the population of interest tended to be the general population. Due to the ecological nature as well as the use of routine data of the included studies, exact demographic characteristics were often not provided. Selected studies, however, did assess specific subsets of the population, notably children under the ages of 1 year (Tanaka, 2015), 3 years (Hasunuma et al., 2014), 14 years (Sajjadi and Bridgman, 2011) and 17 years (El-Zein et al., 2007). One study specifically assessed individuals over the age of 65 years (Sajjadi and Bridgman, 2011).

4.1.5. Interventions and comparisons

Among the 38 unique interventions assessed in the 42 included studies, 5 aimed to reduce ambient air pollution from industrial sources, 7 from residential sources, 22 from vehicular sources, and 4 from multiple sources. Each of these broad intervention categories, however, consists of a wide range of intervention types. In all studies, the comparison against which the intervention was compared can be considered no intervention or practice as usual. The interventions are summarized below, and described in detail in Appendix 1 in the Supplementary material.

The level of intervention implementation varied substantially across included studies (Appendix 1, Supplementary material), from national level (four interventions), to regional level (nine interventions), city/community level (twenty-two interventions), and street level (three interventions).

The timing and duration of the interventions is another important aspect to consider. Some measures, e.g. the construction of a tunnel (Cowie et al., 2012) or a permanent even–odd vehicle ban (Davis, 2008), aimed to permanently improve air quality, while more temporary measures, e.g. traffic reduction strategies during the 1996 Atlanta Olympic Games (Peel et al., 2010) or measures to reduce vehicle traffic and industrial pollution during the 2008 Beijing Olympic Games (Li et al., 2011), were designed to have a temporary impact. Other interventions also had an intermittent effect, as they were only active during certain times, for example when pollution levels were predicted to be above a certain threshold (Mullins and Bharadwaj, 2014). Another important aspect of timing involves seasonal implementation; most interventions remained in place regardless of season, while others were implemented or only expected to impact air quality during the higher pollution winter season. Such examples include California's winter-time oxygenated fuels program (Dolislager, 1997) and those targeting heating practices (Allen et al., 2009; Dockery et al., 2013; Johnston et al., 2013; Yap and Garcia, 2015).

4.1.6. Outcomes

Of the 38 unique interventions, only 18 were evaluated with respect to their effect on health outcomes, and 27 were assessed with respect to their effect on air quality outcomes (Table 2).

4.1.7. Study designs

It should be noted that many included studies did not define or report an exact study design, meaning that a study design label was assigned by review authors. Additionally, in several included studies there was a stark discrepancy between the data collection and the analysis, also rendering the definition of study design more complicated. The study designs are listed in Table 2.

With respect to health outcomes, nine studies applied a cITS-EPOC study design (Deschênes et al., 2012; Pope et al., 2007; Sajjadi et al., 2012; Tanaka, 2015; Dockery et al., 2013; Johnston et al., 2013; Yorifuji et al., 2016), five studies applied an ITS-EPOC study design (Yap and Garcia, 2015; El-Zein et al., 2007; Li et al., 2011; Mullins and Bharadwaj, 2014; Peel et al., 2010), two studies applied a CBA-EPOC study design (Hasunuma et al., 2014; Zigler et al., 2016), and one study applied a CBA study design not adhering to the EPOC criteria (Burr et al., 2004).

With respect to air quality outcomes, three studies applied a cITS-EPOC study design (Bel and Rosell, 2013; Cowie et al., 2012; Deschênes et al., 2012), ten studies applied an ITS-EPOC study design (Bel and Rosell, 2013; Butler et al., 2011; Davis, 2008; Dolislager, 1997; Gallego et al., 2013; Mullins and Bharadwaj, 2014; Sajjadi et al., 2012; Viard and Fu, 2015; Yap and Garcia, 2015), eight studies applied a CBA-EPOC

Table 2
The characteristics of each of the 42 studies, stratified by intervention category.

Intervention number and study ID	Setting: country and location	Population description and sampling	Intervention sub-category	Air quality outcomes	Health outcomes	Study design
Industrial sources						
Intervention 1 Butler 2011/ Deschenes 2012/ Lin 2013	USA Mixed Urban/Rural Areas of the Eastern and Midwestern USA	Population: Residents of the states of interest Sampling: Data on all deaths assessed	Cap and trade program	O3	All-cause mortality; Cardiovascular mortality; Respiratory mortality/ Respiratory hospital admissions	ITS-EPOC/ cITS-EPOC /ITS-EPOC
Intervention 2 Pope 2007	USA Mixed Urban/Rural Southwest USA states: Nevada, Utah, New Mexico, Arizona	Population: Residents of the four SW states Sampling: Data on all hospital admissions assessed	Factory closure	NA	All-cause mortality	cITS-EPOC
Intervention 3 Saaroni 2010	Israel Urban Tel Aviv metropolitan area	NA	Power plant conversion	PM10; NOx; NO2; NO SO2	NA	CBA
Intervention 4 Sajjadi 2011/ Sajjadi 2012	Australia Mixed Urban/Rural Lower Hunter region of New South Wales	Population: Residents in the Lower Hunter region hospital catchment area Sampling: Data on all hospital admissions assessed All ages: respiratory disease; 0–14 yr: asthma 65 + yr: COPD	Factory closure	PM10; PM2.5; NO2; SO2	Respiratory disease hospital admissions; Asthma hospital admissions; COPD hospital admissions	cITS-EPOC [AQ]/ITS-EPOC [health]
Intervention 5 Tanaka 2015	China Urban Several cities spread across China	Population: Infants up to 1 year old from included prefecture Sampling: Data on all infant deaths assessed	Industry requirements	NA	All-cause mortality	CBA-EPOC
Residential sources						
Intervention 6 Allen 2009	Canada Rural Smithers and Telkwa, communities in British Columbia	NA	Stove exchange	PM2.5	NA	CBA
Interventi Aung 2016	India Rural Village in Karnataka, southern India	NA	Stove exchange	PM2.5; BC	NA	CBA
Intervention 8 Dockery 2013a/ Clancy 2002	Ireland Urban Dublin city-wide	Population: Residents of the twelve cities of interest and control cities Sampling: Data on all deaths assessed	Coal ban	NA	All-cause mortality; Cardiovascular mortality; Respiratory mortality	cITS-EPOC/ cITS-EPOC
Intervention 9 Dockery 2013b	Ireland Urban Cork city-wide	Population: Residents of the twelve cities of interest and control cities Sampling: Data on all deaths assessed	Coal ban	NA	All-cause mortality; Cardiovascular mortality; Respiratory mortality; Cardiovascular hospital admissions; Respiratory hospital admission	cITS-EPOC
Intervention 10 Dockery 2013c	Ireland Urban Limerick City and County, Louth, Wexford and Wicklow	Population: Residents of the twelve cities of interest and control cities Sampling: Data on all deaths assessed	Coal ban	NA	All-cause mortality; Cardiovascular mortality; Respiratory mortality; Cardiovascular hospital admissions; Respiratory hospital admission	cITS-EPOC
Intervention 11 Johnston 2013	Australia Urban Launceston, Tasmania city-wide	Population: Residents of Launceston city Sampling: Data on all deaths assessed	Stove exchange	NA	All-cause mortality; Cardiovascular mortality; Respiratory mortality	cITS-EPOC
Intervention 12 Yap 2015	USA Mixed urban/rural California's San Joaquin Valley Air Basin	Population: Adult residents of the San Joaquin Valley Air Basin Sampling: Data on all hospitalizations assessed	Wood burning ban	PM2.5; Coarse particles	Cardiovascular hospital admissions; Respiratory hospital admissions	ITS-EPOC
Vehicular sources						
Intervention 13 Atkinson 2009	UK Urban London metropolitan area	NA	Charging scheme	PM10; NOx; NO2; NO CO; O3	NA	CBA

(*continued on next page*)

Table 2 (*continued*)

Intervention number and study ID	Setting: country and location	Population description and sampling	Intervention sub-category	Air quality outcomes	Health outcomes	Study design
Intervention 14 Bel 2013a	Spain Urban Barcelona metropolitan area	NA	Speed limit change	PM10; NOx	NA	cITS-EPOC
Intervention 15 Bel 2013b	Spain Urban Barcelona metropolitan area	NA	Speed limit change	PM10; NOx	NA	cITS-EPOC
Intervention 16 Boogaard 2012	Netherlands Urban City centers of Amsterdam, the Hague, Den Bosch, Tilburg, Utrecht	NA	Low emission zone	PM10; PM2.5; NOx; NO2; Soot	NA	CBA-EPOC
Intervention 17 Burr 2004	UK Urban Small town in Northern Wales	Population: Residents and workers both in the intervention and a control street Sampling: Not specified	Infrastructure changes	PM10; PM2.5	Respiratory symptoms; Lung function	CBA
Intervention 18 Carrillo 2013	Ecuador Urban Quito metropolitan area	NA	Even-odd restriction	CO	NA	CBA-EPOC
Intervention 19 Cowie 2012	Australia Urban Local, primarily residential area of Sydney	NA	Tunnel construction; Road restructuring	PM10; PM2.5; NOx; NO2	NA	cITS-EPOC
Intervention 20 Dijkema 2008	Netherlands Urban Amsterdam metropolitan area	NA	Speed limit change	PM10; BS; NOx	NA	CBA
Intervention 21 Dolislager 1997	USA Urban Four metropolitan areas in California	NA	Fuel requirements	CO	NA	ITS-EPOC
Intervention 22 El-Zein 2007	Lebanon Urban Beirut city-wide	Population: Children in Beirut under 17 years Sampling: All hospital admissions from accredited hospitals assessed	Diesel vehicle ban	NA	Respiratory hospital admissions	ITS-EPOC
Intervention 23 Fensterer 2014/ Morfeld 2013	Germany Urban Munich city center	NA	Low emission zone	PM10	NA	CBA-EPOC/ CBA
Intervention 24 Gallego 2013a/ Davis 2008	Mexico Urban Mexico City metropolitan area	NA	Even-odd restriction	NOx; NO2; O3; SO2; CO	NA	ITS-EPOC/ITS-EPOC
Intervention 25 Gallego 2013b/ Gramsch 2013	Chile Urban Santiago metropolitan area	NA	Public transport restructuring	CO; BC	NA	ITS-EPOC/CBA
Intervention 26 Hasunuma 2014	Japan Mixed Urban/Rural Areas spread across Japan	Population: Children 3 years old living in the 28 survey areas Sampling: Not specified	Required vehicle standards	NO2	Respiratory symptoms	CBA-EPOC
Intervention 27 Kim 2011	South Korea Urban Several cities spread across South Korea	NA	Clean fuel use	PM10; NO2	NA	CBA-EPOC
Intervention 28 Morfeld 2014	Germany Urban 17 German cities	NA	Low emission zone	NOx; NO2; NO	NA	CBA-EPOC
Intervention 29 Peel 2010/ Friedman 2001	USA Urban Atlanta metropolitan area	Population: Residents of Atlanta and control areas Sampling: Data on all emergency department visits assessed	Comprehensive traffic reduction strategy	NOx; NO2; O3; SO2; CO	Asthma emergency department (ED) visits; Pneumonia ED visits; COPD ED visits; CVD ED visits	cITS-EPOC [health] CBA-EPOC [AQ]/cITS-EPOC [health] CBA-EPOC [AQ]
Intervention 30 Ruprecht 2009	Italy Urban Milan city center	NA	Charging scheme	PM10	NA	CBA
Intervention 31 Titos 2015a	Slovenia Urban Ljubljana metropolitan area	NA	Road restructuring	BC	NA	CBA

(*continued on next page*)

Table 2 (*continued*)

Intervention number and study ID	Setting: country and location	Population description and sampling	Intervention sub-category	Air quality outcomes	Health outcomes	Study design
Intervention 32 Titos 2015b	Spain Urban Granada metropolitan area	NA	Public transport restructuring	BC	NA	CBA
Intervention 33 Viard 2015	China Urban Beijing metropolitan area	NA	Even-odd restriction	PM10	NA	ITS-EPOC
Intervention 34 Yorifuji 2016/ Yorifuji 2011	Japan Urban Tokyo metropolitan area	Population: Residents of Tokyo Sampling: Data on all deaths assessed	Required vehicle standards	PM2.5; NO2	All-cause mortality; Cardiovascular mortality; Respiratory mortality; Cerebrovascular mortality; Mortality from other causes	cITS-EPOC/ ITS-EPOC
Multiple sources						
Intervention 35 Giovanis 2014	USA Mixed Urban/Rural Charlotte, North Carolina and surrounding area	NA	Repeated coordinated measures	O3	All-cause mortality	CBA-EPOC
Intervention 36 Li 2011	China Urban Beijing metropolitan area	Population: Adult residents of Beijing admitted to hospitals for asthma events Sampling: Data on all admissions assessed	Even-odd restriction; Vehicle restriction; Power plant restriction	NA	Asthma	ITS-EPOC
Intervention 37 Mullins 2014	Chile Urban Santiago metropolitan area	NA	Repeated coordinated measures	PM10	NA	ITS-EPOC
Intervention 38 Zigler 2016	USA Mixed Urban/Rural Western states	NA	Tailored selection of measures	PM10	All-cause mortality; Cardiovascular hospital admissions; Respiratory hospital admissions	CBA-EPOC

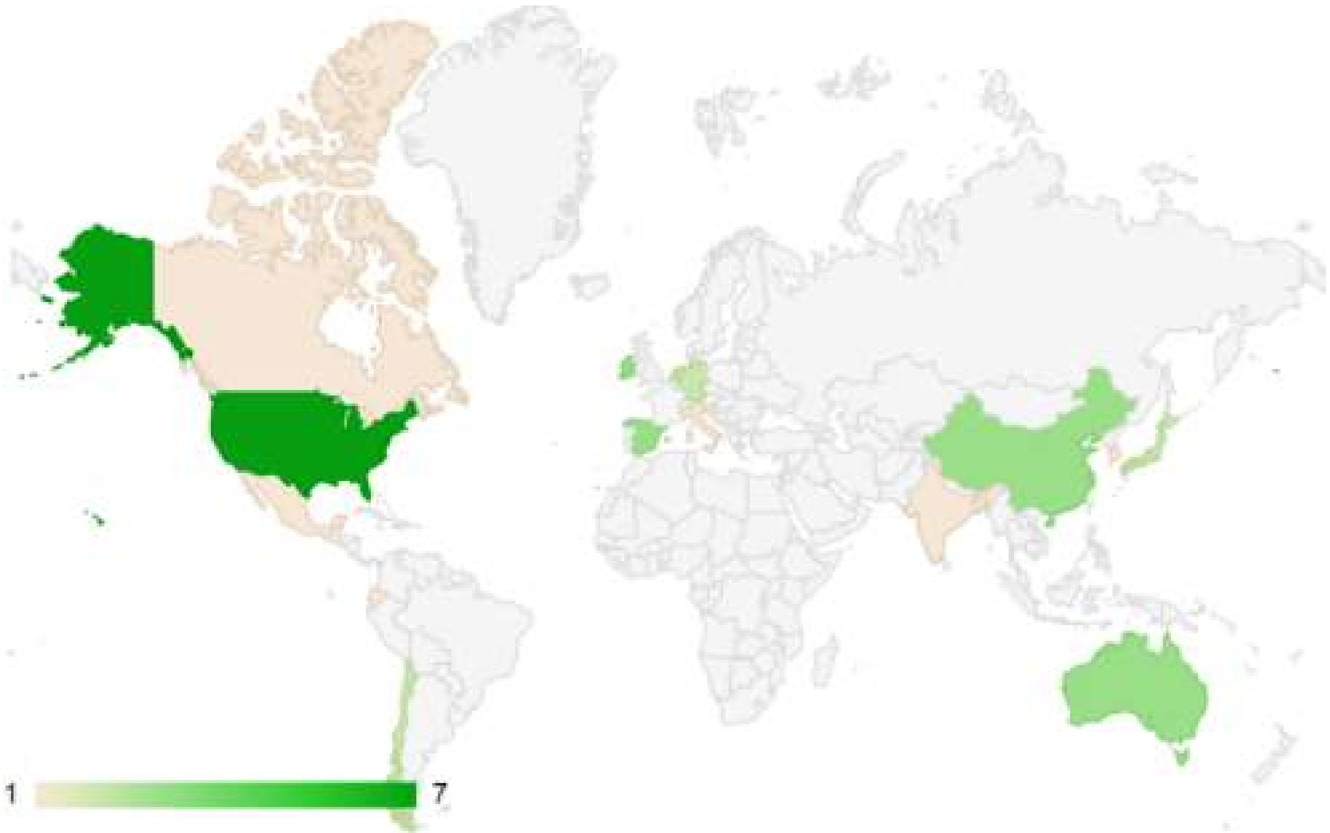


Fig. 2. Geographical location of the 38 interventions, with frequency indicated by color/shading.

study design (Boogaard et al., 2012; Carrillo et al., 2016; Giovanis, 2014; Hasunuma et al., 2014; Kim and Shon, 2011; Morfeld et al., 2014; Peel et al., 2010; Zigler et al., 2016), and eleven applied a CBA study design not adhering to the EPOC criteria (Allen et al., 2009; Aung et al., 2016; Burr et al., 2004; Dijkema et al., 2008; Gramsch et al., 2013; Fensterer et al., 2014; Ruprecht and Invernizzi, 2009; Saaroni et al., 2010; Titos et al., 2015; Yorifuji et al., 2016).

4.2. Internal and external validity

Using the NICE-modified GATE tool, we assessed the risk of bias (i.e. internal validity) and external validity of all included studies. These overall judgements can be found in Fig. 3 for studies assessing health (left side) and air quality (right side) outcomes. With respect to health outcomes, we appraised 11 studies (58%) as (+ +), four studies (21%) as (+), and four studies (21%) as (−). With respect to air quality outcomes, we judged 10 studies (29%) as (+ +), 17 studies (49%) as (+), and eight studies (23%) as (−).

For detailed judgements on the individual criteria for each included study, see the full review. In short, regarding health outcomes, several studies inappropriately selected covariates, employing a convenience selection of covariates, without justifying or discussing the implications of this selection (Deschênes et al., 2012; Dockery et al., 2013; El-Zein et al., 2007; Sajjadi and Bridgman, 2011; Yap and Garcia, 2015; Yorifuji et al., 2016). The analysis methods of several studies, especially those assessing vehicular interventions, likely also introduced bias, where, for example, models were not adjusted or poorly adjusted, analyses were under-powered, or effect estimates and/or measures of precision were reported insufficiently (Burr et al., 2004; El-Zein et al., 2007; Hasunuma et al., 2014; Johnston et al., 2013; Sajjadi and Bridgman, 2011; Yap and Garcia, 2015; Aung et al., 2016).

With respect to air quality outcomes, several studies likely introduced bias through the selection of intervention and control sites (Aung et al., 2016; Bel and Rosell, 2013; Kim and Shon, 2011; Saaroni et al., 2010). As described above for health outcomes, several studies inappropriately selected covariates, employing a convenience selection without justifying or discussing the implications of this selection (Aung et al., 2016; Cowie et al., 2012; Davis, 2008; Deschênes et al., 2012; Gallego et al., 2013; Gramsch et al., 2013; Ruprecht and Invernizzi, 2009; Sajjadi et al., 2012; Saaroni et al., 2010; Yorifuji et al., 2016). Several studies, especially those assessing vehicular interventions, did not report the completeness of outcome data, or were missing a meaningful proportion of outcome data (Aung et al., 2016; Bel and Rosell, 2013; Burr et al., 2004; Cowie et al., 2012; Kim and Shon, 2011; Ruprecht and Invernizzi, 2009; Sajjadi et al., 2012). There were concerns with the analysis methods of several studies, with regard to the choice of statistical test, model selection, model adjustment, study power, and the overall poor reporting of effect estimates and precision (Allen et al., 2009; Aung et al., 2016; Bel and Rosell, 2013; Burr et al., 2004; Gramsch et al., 2013; Hasunuma et al., 2014; Kim and Shon, 2011; Ruprecht and Invernizzi, 2009; Saaroni et al., 2010; Titos et al., 2015; Yorifuji et al., 2016).

Both for studies assessing health outcomes and studies assessing air quality outcomes, there were no substantial concerns with external validity..

4.3. Effects of interventions

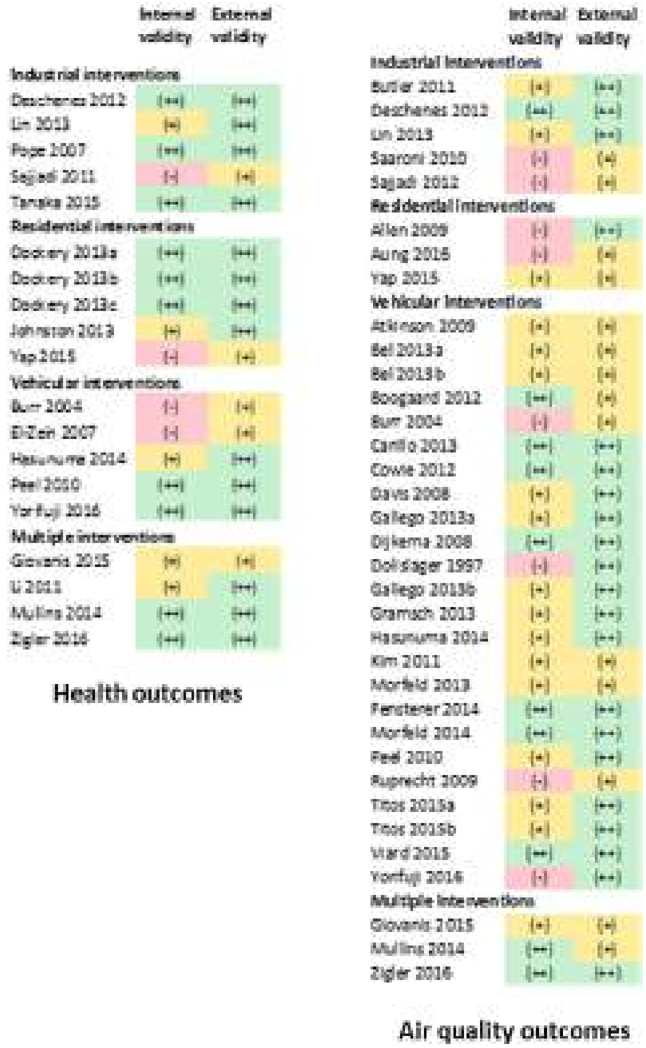
The summary of findings tables, which also include the full GRADE assessment, can be found in the full review. In brief, for all intervention categories and primary outcomes, the evidence was of either low or very low certainty. These ratings were primarily driven by the nature of the applied study designs; all included studies applied a non-randomized study design to evaluate the respective intervention, and these study designs always begin the GRADE assessment as 'low certainty'. Further concerns related to risk of bias and inconsistency also influenced the GRADE ratings.

Our detailed reporting of effects, below, are organized by type of intervention. For each category the findings for health and air quality are synthesized narratively and graphically using harvest plots.

4.3.1. Industrial interventions vs practice as usual

For the evidence synthesis of interventions to reduce ambient air pollution from industrial sources, five studies contributed evidence on health outcomes and four studies contributed evidence on air quality outcomes. As illustrated in Fig. 4, observed associations between interventions and both health (top panel) and air quality (bottom panel) outcomes were mixed, with the majority of studies observing either no clear association or a significant association in favor of the intervention. The reported effect estimates as well as reported data on uncertainty and/or statistical significance can be found in Table 3.

With regard to health outcomes, Deschênes et al. (2012) (Intervention 1) observed no clear change in all-cause mortality or cardiovascular mortality associated with the US NO_x Budget cap and trade program. Lin et al. (2013) (Intervention 1) also assessed the US NO_x Budget cap and trade program, but only for New York state, and



	Internal validity	External validity
Industrial interventions		
Deschenes 2012	(++)	(++)
Lin 2013	(+)	(++)
Pope 2007	(++)	(++)
Sajjadi 2011	(-)	(+)
Tanaka 2015	(++)	(++)
Residential interventions		
Dockery 2013a	(++)	(++)
Dockery 2013b	(++)	(++)
Dockery 2013c	(++)	(++)
Johnston 2013	(+)	(++)
Yap 2015	(-)	(+)
Vehicular interventions		
Burr 2004	(-)	(+)
El-Zein 2007	(-)	(+)
Hasunuma 2014	(+)	(++)
Peel 2010	(++)	(++)
Yorifuji 2016	(++)	(++)
Multiple interventions		
Giovanis 2015	(+)	(+)
Li 2011	(+)	(++)
Mullins 2014	(++)	(++)
Zigler 2016	(++)	(++)

Health outcomes

	Internal validity	External validity
Industrial interventions		
Butler 2011	(+)	(++)
Deschenes 2012	(++)	(++)
Lin 2013	(+)	(++)
Saaroni 2010	(-)	(+)
Sajjadi 2012	(-)	(+)
Residential interventions		
Allen 2009	(-)	(++)
Aung 2016	(-)	(+)
Yap 2015	(+)	(+)
Vehicular interventions		
Atkinson 2009	(+)	(+)
Bel 2013a	(+)	(+)
Bel 2013b	(+)	(+)
Boogaard 2012	(++)	(+)
Burr 2004	(-)	(+)
Carrillo 2013	(++)	(++)
Cowie 2012	(++)	(++)
Davis 2008	(+)	(++)
Gallego 2013a	(+)	(++)
Dijkema 2008	(++)	(++)
Dolislager 1997	(-)	(++)
Gallego 2013b	(+)	(++)
Gramsch 2013	(+)	(++)
Hasunuma 2014	(+)	(++)
Kim 2011	(+)	(+)
Morfeld 2013	(+)	(+)
Fensterer 2014	(++)	(++)
Morfeld 2014	(++)	(++)
Peel 2010	(+)	(++)
Ruprecht 2009	(-)	(+)
Titos 2015a	(+)	(++)
Titos 2015b	(+)	(++)
Viard 2015	(++)	(++)
Yorifuji 2016	(-)	(++)
Multiple interventions		
Giovanis 2015	(+)	(+)
Mullins 2014	(++)	(+)
Zigler 2016	(++)	(++)

Air quality outcomes

Fig. 3. Overall judgements of internal and external validity for included studies. (+ +) indicates that all or most of the checklist criteria have been fulfilled; where they have not been fulfilled the conclusions are very unlikely to alter. (+) indicates that some of the checklist criteria have been fulfilled; where they have not been fulfilled, or are not adequately described, the conclusions are unlikely to alter. (−) indicates that few or no checklist criteria have been fulfilled and the conclusions are likely or very likely to alter.

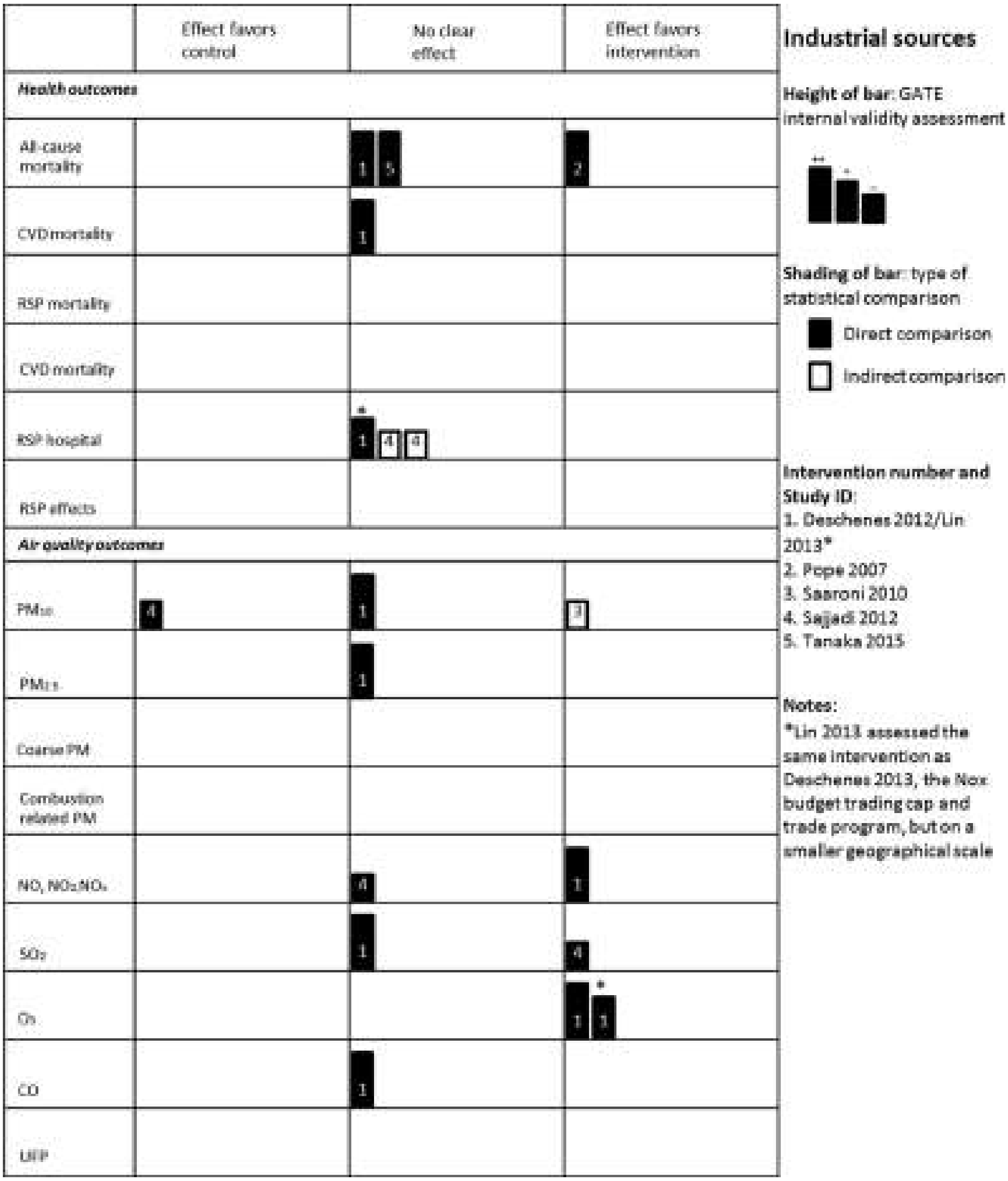


Fig. 4. Harvest plots summarizing effects of interventions targeting industrial sources on health (top panel) and air quality (bottom panel) outcomes.

observed no clear change in respiratory hospitalizations associated with the intervention. Pope et al. (2007) (Intervention 2) evaluated the temporary closure of copper smelters in the US Southwest due to a strike, and observed a significant decrease in all-cause mortality. Sajjadi and Bridgman (2011) (Intervention 4) observed similar changes at both intervention and control sites in COPD hospitalizations in the elderly (aged 65+) and asthma in children (aged < 15) associated with the permanent closure of a local steel works in Australia. Tanaka (2015) (Intervention 5) observed no clear change in infant mortality associated with the Chinese Two Zone Control policy.

With regard to air quality outcomes, Deschênes et al. (2012) (Intervention 1) observed no clear change in PM$_{10}$, PM$_{2.5}$, SO$_2$ or CO, and a significant decrease in NO$_2$ and O$_3$ associated with the US NO$_x$ Budget cap and trade program. Lin et al. (2013) (Intervention 1), for the US NO$_x$ Budget cap and trade program in New York state, observed a significant decrease in O$_3$. Saaroni et al. (2010) (Intervention 3) observed a significant decrease in PM$_{10}$ concentrations associated with the conversion of a Tel Aviv power station from oil to gas. Sajjadi et al. (2012) (Intervention 4) observed a significant increase in PM$_{10}$, no clear change in NO$_2$, and a significant decrease in SO$_2$ associated with the permanent closure of a local steel works in Australia.

4.3.2. *Residential interventions vs practice as usual*

For the evidence synthesis of interventions to reduce ambient air pollution from residential sources, five studies contributed evidence on health outcomes and three studies contributed evidence on air quality outcomes. As illustrated in Fig. 5, observed associations between the interventions and both health (top panel) and air quality (bottom panel) outcomes were mixed, with all studies observing either a significant association favoring the intervention or no clear association. The reported effect estimates as well as reported data on uncertainty and/or statistical significance can be found in Table 4.

With regard to health outcomes, three studies assessed the effectiveness of coal ban interventions in Dublin (Dockery et al., 2013), in Cork (Dockery et al., 2013) and in five smaller Irish cities (Dockery et al., 2013). The 1990 coal ban in Dublin (Intervention 8) was

Table 3
Reported effect estimates from studies assessing interventions targeting industrial sources.

Study and intervention	Outcome	Effect estimate	Reported measure of variability or statistical significance	Narrative description
Intervention 1 Deschenes 2012/Lin 2013*: Cap and trade program	AC mortality	DiD estimator = −1.557	SE = −0.813 p-value > 0.05	No clear change (1.557 fewer deaths per 100,000 population)
	CV mortality	DiD estimator = −0.547	SE = 0.675 p-value > 0.05	No clear change (0.547 fewer deaths per 100,000 population)
	RSP hospital*	Adj % change = −0.15	95% CI = (−9.83; 10.55)	No clear change (0.15% reduction)
	PM_{10}	DiD estimator = −0.896	SE = 1.018 p-value > 0.05	No clear change (3.0% decrease)
	$PM_{2.5}$	DiD estimator = −0.382	SE = 0.278 p-value > 0.05	No clear change (2.3% decrease)
	NO_2	DiD estimator = −1.210	SE = 0.397 p-value < 0.01	Significant 7.2% decrease
	SO_2	DiD estimator = 0.097	SE = 0.183 p-value > 0.05	No clear change (2.1% increase)
	O_3	DiD estimator = −2.965	SE = 0.747 p-value < 0.01	Significant 5.8% reduction at the intervention relative to the control site
	O_3*	Adj % change = −2.47	95% CI = (−3.22; −1.72) p-value < 0.05	Significant 2.5% reduction
	CO	DiD estimator = −0.042	SE = 0.035 p-value > 0.05	No clear change (8.1% decrease)
Intervention 2 Pope 2007: Factory closure	AC mortality	Adj % change = −2.5	95% CI = (−4.0; −1.1)	Significant 2.5% decrease
Intervention 3 Saaroni 2010 Power plant conversion	PM_{10}	NR (descriptive statistics show concentration decrease)	p-value < 0.05	Concentrations decreased at intervention site (14%), while they increased at control sites (31%)
Intervention 4 Sajjadi 2012: Factory closure	RSP hospital (COPD, age > 64)	Adj % change Int = 36.9 Con = 31.5	p-value Int < 0.0001 Con = 0.0003	A large, significant increase observed at both intervention (36.9%) and control (31.5%) sites
	RSP hospital (asthma, age < 15)	Adj % change Int = −34.1 Con = −36.6	p-value Int = 0.0031 Con = 0.0008	A large, significant decrease observed at both intervention (34.1%) and control (36.6%) sites
	PM_{10}	% change = 13.2	p-value = 0.021	Significant 13.2% increase
	NO_2	% change = −3.3	p-value > 0.05	No clear change (3.3% decrease)
	SO_2	% change = −40.5	p-value < 0.0001	Significant 40.5% decrease
Intervention 5 Tanaka 2015: Industry requirements	AC mortality (infants)	DiD estimator = −3.287	SE = 2.218 p-value > 0.05	No clear change (3.3 fewer deaths per 1000 live births)

Abbreviations: all-cause (AC); cardiovascular (CV); respiratory (RSP); difference-in-differences (DiD); standard error (SE); adjusted (Adj); intervention (Int); control (Con).

associated with a significant reduction in respiratory mortality, but no clear change was observed for all-cause mortality or cardiovascular mortality. In Cork (Intervention 9), no clear changes were observed for all-cause mortality, cardiovascular mortality, respiratory mortality, cardiovascular hospitalizations or respiratory hospitalizations associated with the coal ban. In the five smaller Irish cities (Intervention 10), no clear changes were observed for all-cause mortality, cardiovascular mortality or respiratory mortality associated with the coal ban. It was, however, associated with a significant decrease in cardiovascular hospitalizations and respiratory hospitalizations. Johnston et al. (2013) (Intervention 11) observed no clear change in all-cause mortality, cardiovascular mortality or respiratory mortality associated with a stove exchange program in Tasmania (Australia). Yap and Garcia (2015) (Intervention 12) observed a significant decrease in cardiovascular hospitalizations in the population over 65 years of age, yet no clear change in the population under 65 years of age associated with an intermittent, air-quality-dependent wood burning ban in the San Joaquin Valley of California. The study also observed no clear change in respiratory hospitalizations in either the population over 65 years of age or the population under 65 years of age associated with the wood burning ban.

With regard to air quality outcomes, Allen et al. (2009) (Intervention 6) observed no clear change in $PM_{2.5}$ concentrations associated with a stove exchange program in British Columbia (Canada). Aung et al. (2016) (Intervention 7) observed no clear change in $PM_{2.5}$ or BC concentrations associated with a stove exchange program in southern India. It should be noted, however, that these interventions primarily aimed to improve indoor air quality; it is unclear to what extent changes in outdoor concentrations could be expected given the scale of the implementation. Yap and Garcia (2015) (Intervention 12) observed a significant decrease in $PM_{2.5}$ concentrations and coarse PM associated with an intermittent, air-quality-dependent wood burning ban in the San Joaquin Valley of California.

4.3.3. Vehicular interventions vs practice as usual

For the evidence synthesis of interventions to reduce ambient air pollution from vehicular sources, five studies contributed evidence on health outcomes and nineteen studies contributed evidence on air quality outcomes. As illustrated in Fig. 6, observed associations between interventions and both health (top panel) and air quality (bottom panel) outcomes were mixed, with most studies observing either no clear association in either direction or a significant association in favor of the intervention. A small number of studies observed a significant association favoring the control. The reported effect estimates as well as reported data on uncertainty and/or statistical significance can be found in Table 5.

With regard to health outcomes, Burr et al. (2004) (Intervention 17) observed no clear change in asthma symptoms associated with the opening of a bypass to reduce traffic congestion in Northern Wales. El-Zein et al. (2007) (Intervention 22) observed a slight yet significant immediate reduction, yet no longer-term change in respiratory hospitalizations in children under 14 associated with a ban on diesel

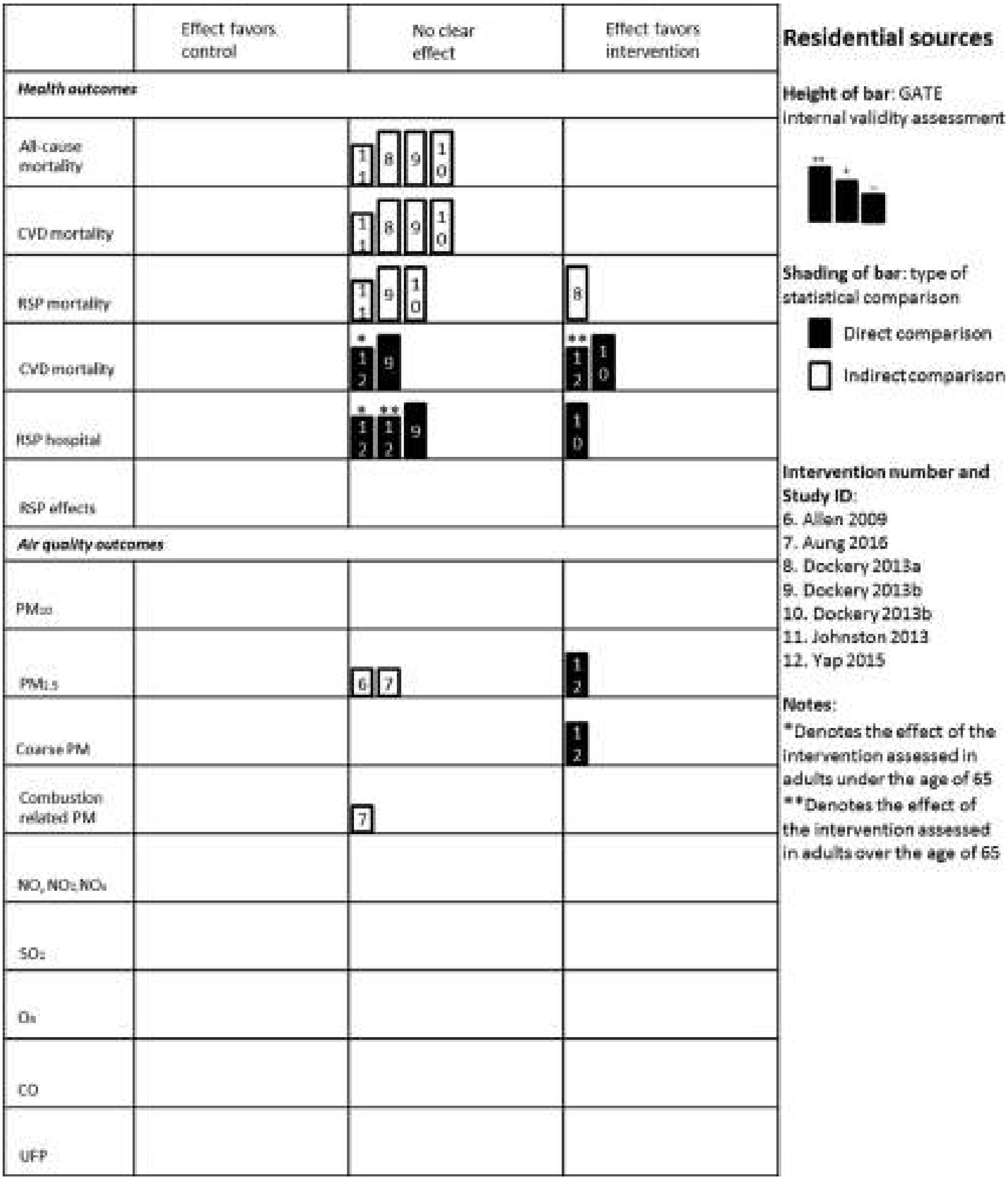


Fig. 5. Harvest plots summarizing effects of interventions targeting residential sources on health (top panel) and air quality (bottom panel) outcomes.

automobiles in Beirut, Lebanon. Hasunuma et al. (2014) (Intervention 26) observed a significant decrease in respiratory symptoms in children three years old or younger associated with standards required by the NOx/PM Law in Japan. Peel et al. (2010) (Intervention 29) observed no clear change in cardiovascular hospitalizations or respiratory hospitalizations associated with the coordinated measures aimed at reducing traffic during the 1996 Atlanta Olympic Games. Yorifuji et al. (2016) (Intervention 34) observed a significant decrease in all-cause mortality, cardiovascular mortality and respiratory mortality associated with mandatory standards for diesel vehicles entering the Tokyo metropolitan area.

With regard to air quality outcomes, two studies evaluated congestion charging schemes. Atkinson et al. (2009) (Intervention 13) observed no clear change in PM_{10}, NOx, NO_2 or NO concentrations at streetside sites associated with the London congestion charging scheme. Ruprecht and Invernizzi (2009) (Intervention 30) observed no clear change in PM_{10} concentrations associated with the Ecopass congestion charging scheme in Milan, Italy. Several studies assessed LEZs in Europe. Boogaard et al. (2012) (Intervention 16) observed no clear change in PM_{10}, soot or NOx, a significant decrease in $PM_{2.5}$, and a significant increase in NO_2 associated with multiple low emission zones in the Netherlands. Fensterer et al. (2014) (Intervention 23) observed a significant decrease in PM_{10} concentrations associated with the low emission zone in Munich, Germany, both in summer and winter. Morfeld et al. (2014) (Intervention 28) observed a significant decrease in NO_x, NO_2 and NO concentrations associated with LEZs in 17 German cities. Multiple studies also assessed even-odd bans in cities across the world. Davis (2008) (Intervention 24) observed a significant increase in NO_x concentrations, an increase in NO_2 concentrations, and an increase in O_3 concentrations, yet no clear change in SO_2 concentrations

Table 4
Reported effect estimates from studies assessing interventions targeting residential sources.

Study	Outcome	Effect estimate	Reported measure of variability or statistical significance	Narrative description
Intervention 6 Allen 2009: Stove exchange	$PM_{2.5}$	Median change Int = −2.7 ug/m^3 Con = −3.4 ug/m^3	p-value Int = 0.04 Con = 0.03	No clear change (significant reduction in median concentration at both intervention and control sites)
Intervention 7 Aung 2016: Stove exchange	$PM_{2.5}$	Mean diff Pre-int = 13 Post-int = 18	p-value Pre-int < 0.05 Post-int > 0.05	No clear change (concentrations increased at both intervention and control sites)
	BS	Mean diff Pre-int = 2.7 Post-int = 1.6	p-value Pre-int < 0.05 Post-int > 0.05	No clear change (concentrations increased at both intervention and control sites)
	RSP hospital	Adj % change Int = −8.5 Con = 4.8	95% CI Int = (–23.2; 9.0) Con = (−7.4; 18.6)	No clear change (8.5% decrease at intervention sites; 4.8% increase at control sites)
Intervention 8 Dockery 2013a: Coal ban	AC mortality	Adj % change Int = −1.0 Con = −2.7	95% CI Int = (−6.0; 4.4) Con = (−7.7; 2.7)	No clear change (1.0% decrease at intervention sites; 2.7% decrease at control sites)
	CV mortality	Adj % change Int = 0.1 Con = −1.8	95% CI Int = (−8.5; 9.5) Con = (−10.0; 7.2)	No clear change (0.1% increase at intervention sites; 1.8% decrease at control sites)
	RSP hospital	Adj % change Int = −16.8 Con = −2.3	95% CI Int = (−24.4; −8.4) Con = (−11.5; 7.9)	Significant 16.8% decrease at intervention sites, no clear change (2.3% decrease) at control sites
Intervention 9 Dockery 2013b: Coal ban	AC mortality	Adj % change Int = −4.4 Con = −3.6	95% CI Int = (−9.6; 1.0) Con = (−8.8; 2.0)	No clear change (4.4% decrease at intervention sites; 3.6% decrease at control sites)
	CV mortality	Adj % change Int = −3.7 Con = −3.4	95% CI Int = (−12.2; 5.6) Con = (−12.0; 6.1)	No clear change (3.7% decrease at intervention sites; 3.4% decrease at control sites)
	RSP mortality	Adj % change Int = −9.3 Con = −1.4	95% CI Int = (−18.2; 0.7) Con = (−10.9; 9.1)	No clear change (9.3% decrease at intervention sites; 1.4% decrease at control sites)
	CV hospital	Adj % change = −3.6	95% CI = (−9.8; 2.9)	No clear change (3.6% decrease)
	RSP hospital	Adj % change = 3.6	95% CI = (−2.5; 10)	No clear change (3.6% increase)
Intervention 10 Dockery 2013c: Coal ban	AC mortality	Adj % change Int = 0.2 Con = −0.2	95% CI Int = (−3.1; 3.6) Con = (−6.7; 6.8)	No clear change (0.2% increase at intervention sites; 0.2% decrease at control sites)
	CV mortality	Adj % change Int = −1.1 Con = −3.1	95% CI Int = (−6.1; 4.1) Con = (−12.6; 7.3)	No clear change (1.1% decrease at intervention sites; 3.1% decrease at control sites)
	RSP mortality	Adj % change Int = −2.6 Con = 1.4	95% CI Int = (−8.1; 3.4) Con = (−10.4; 14.5)	No clear change (2.6% decrease at intervention sites; 1.4% increase at control sites)
	CV hospital	Adj % change = −3.2	95% CI = (−5.7; −0.6)	Significant 3.2% decrease
	RSP hospital	Adj % change = −8.5	95% CI = (−10.5; −6.2)	Significant 8.5% decrease
Intervention 11 Johnston 2013: Stove exchange	AC mortality	Adj % change Int = −2.7 Con = 1.4	95% CI Int = (−8.7; 3.7) Con = (−3.0; 6.0)	No clear change (2.7% decrease at intervention sites; 1.4% increase at control sites)
Intervention 12 Yap 2015: Wood burning ban	CV mortality	Adj % change Int = −4.9 Con = 0.9	95% CI Int = (−15.5; 7.0) Con = (−7.1; 9.6)	No clear change (4.9% decrease at intervention sites; 0.9% increase at control sites)
	RSP hospital	Adj % change Int = −8.5 Con = 4.8	95% CI Int = (–23.2; 9.0) Con = (−7.4; 18.6)	No clear change (8.5% decrease at intervention sites; 4.8% increase at control sites)
	RSP hospital RSP hospital (COPD, age 45–64)	Adj relative risk = 0.90	95% CI = (0.78; 1.05)	No clear change (10% decrease in risk)
	RSP hospital RSP hospital (COPD, age > 65)	Adj relative risk = 0.93	95% CI = (0.83; 1.04)	No clear change (7% decrease in risk)
	$PM_{2.5}$	Adj % change = −12.3	95% CI = (−14.6; −7.3)	Significant 12.3% decrease
	Coarse PM	Adj % change = −8.5	95% CI = (−11.8; −6.6)	Significant 8.5% decrease

Abbreviations: all-cause (AC); cardiovascular (CV); respiratory (RSP); difference (diff); adjusted (Adj); intervention (Int); control (Con).

associated with Hoy no Circula, an even-odd driving ban in Mexico City. Gallego et al. (2013) (Intervention 24), which also evaluated Hoy no Circula in Mexico City, observed an immediate significant decrease in CO concentrations, yet no clear long-term change in CO concentrations. Carrillo et al. (2016) (Intervention 18) observed a significant decrease in CO concentrations associated with an even-odd driving ban in Quito, Ecuador. Viard and Fu (2015) (Intervention 33) observed a significant decrease in PM_{10} concentrations associated with an even-odd driving restriction policy, which was then relaxed to a one-day per vehicle driving ban in Beijing.

Multiple studies evaluated interventions related to speed limit changes. Bel and Rosell (2013) (Intervention 14) observed a significant increase in PM_{10} and NO_x concentrations associated with a speed limit reduction in Barcelona, Spain. Bel and Rosell (2013) (Intervention 15), in the same study, observed a significant decrease in PM_{10} and in NO_x concentrations associated with an adaptive speed limit scheme in

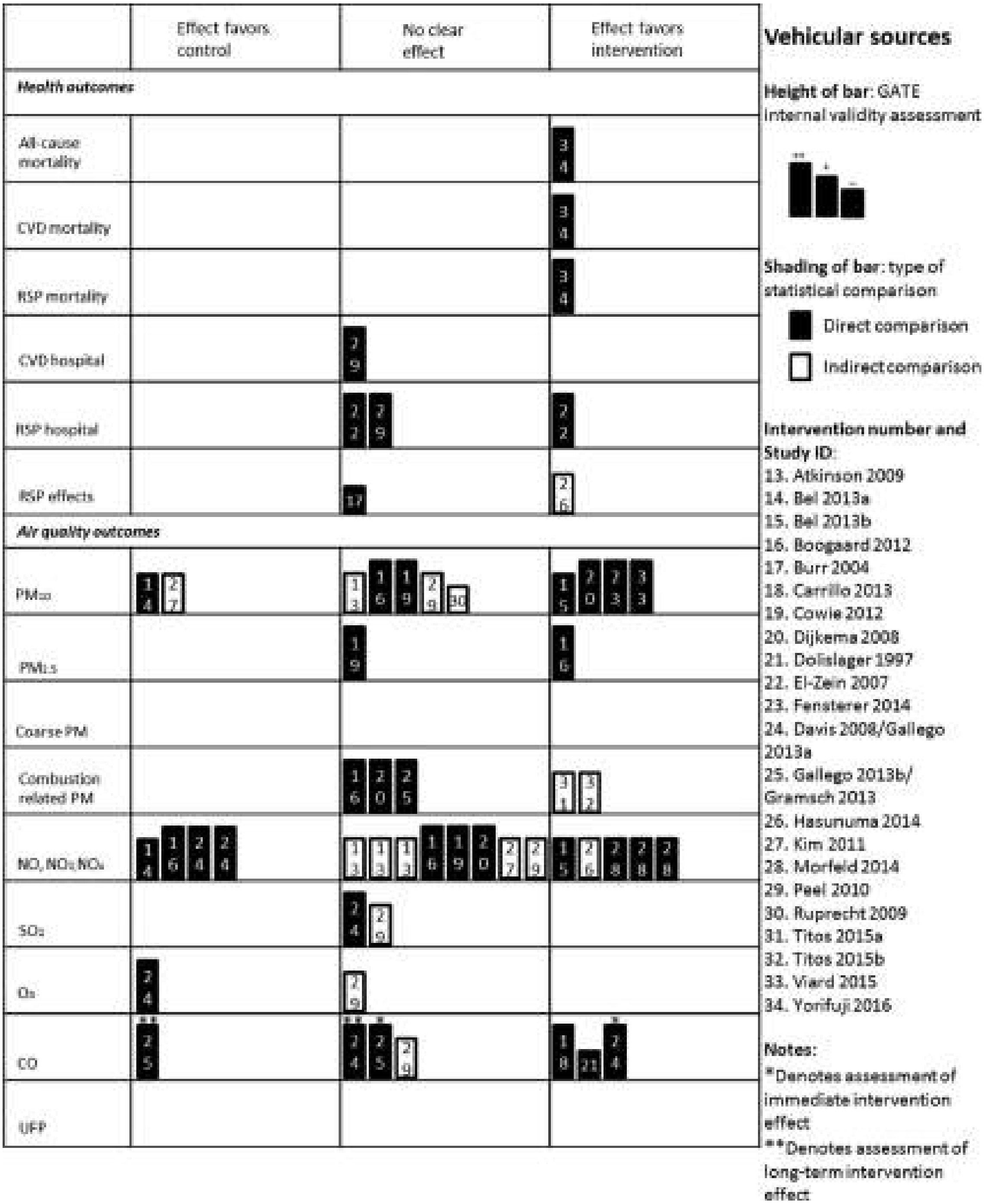


Fig. 6. Harvest plots summarizing effects of interventions targeting vehicular sources on health (top panel) and air quality (bottom panel) outcomes.

Barcelona, Spain. Dijkema et al. (2008) (Intervention 20) observed a significant decrease in PM_{10} concentrations, but no clear change in BS or NO_x concentrations associated with a speed limit reduction on a heavily trafficked roadway in Amsterdam.

Several studies evaluated permanent infrastructure changes. Cowie et al. (2012) (Intervention 19) observed no clear change in PM_{10}, $PM_{2.5}$, NO_x or NO_2 concentrations associated with a tunnel meant to relieve traffic congestion in suburban Sydney, Australia. Gallego et al. (2013) (Intervention 25) evaluated Transantiago, a restructuring of the public transportation system in Santiago, Chile, and observed no clear immediate change, yet did observe a significant long-term increase in CO concentrations. Gramsch et al. (2013) (Intervention 25) also evaluated Transantiago in Santiago, Chile, and observed no clear change in BC. Kim and Shon (2011) (Intervention 27) observed a significant increase in PM_{10} concentrations, yet no clear change in NO_2 concentrations associated with the Natural Gas Vehicle Supply program that led to the introduction of natural gas-powered buses in South Korean cities. Peel et al. (2010) (Intervention 29) observed no clear change in PM_{10}, NO_2, O_3, SO_2 or CO concentrations associated with the coordinated measures aimed at reducing traffic during the 1996 Atlanta Olympic Games. Titos et al. (2015) (Intervention 31) observed a significant decrease in BC concentrations associated with a partial closure and reconstruction of a major street in Ljubljana, Slovenia. Titos et al. (2015) (Intervention 32) observed a significant decrease in BC concentrations associated with the restructuring of the public bus system in Granada, Spain. Multiple studies evaluated changes influencing public transportation systems.

Table 5
Reported effect estimates from studies assessing interventions targeting vehicular sources.

Study	Outcome	Effect estimate	Reported measure of variability or statistical significance	Narrative description
Intervention 13 Atkinson 2009 Charging scheme	PM_{10}	% change Int 1 = 5.6 Int 2 = −15 Con 1 = 2.5 Con 2 = −0.8	NR	No clear change (mixed increases and decreases at intervention and control sites)
	NO_x	% change Int 1 = −5 Int 2 = −6.4 Con 1 = −4.4 Con 2 = −5	NR	No clear change (similar decreases across intervention and control sites)
	NO_2	% change Int 1 = 2.1 Int 2 = 7.1 Con 1 = 3.7 Con 2 = − 2.3	NR	No clear change (slight increases at intervention sites; increase and decrease at control sites)
	NO	% change Int 1 = −9.5 Int 2 = −31 Con 1 = −9.4 Con 2 = −6.6	NR	No clear change (decreases across intervention and control sites)
Intervention 14 Bel 2013a Speed limit change	PM_{10}	DiD estimator = 2.594	p-value < 0.05	Significant 5.4% increase
	NO_x	DiD estimator = 1.887	p-value < 0.01	Significant 1.7% increase
Intervention 15 Bel 2013b Speed limit change	PM_{10}	DiD estimator = − 6.196	p-value < 0.01	Significant 14.7% decrease
	NO_x	DiD estimator = −10.462	p-value < 0.01	Significant 16% decrease
Intervention 16 Boogaard 2012 Low emission zone	PM_{10}	Mean change Int 1 = −3.1 Int 2 = −4.0 Con = −3.3	p-value Int 1 vs. Con > 0.05 Int 2 vs. Con > 0.05	No clear change (11.0% and 15.9% decrease at intervention sites; 14.7% decrease at control sites)
	$PM_{2.5}$	Mean change Int 1 = −5.1 Int 2 = −3.9 Con = −2.7	p-value Int 1 vs. Con < 0.05 Int 2 vs. Con > 0.05	Significant decrease when comparing change at streetside intervention sites (30.4% decrease) to change at control sites (19.6% decrease)
	Soot	Mean change Int 1 = −0.04 Int 2 = −0.13 Con = −0.11	p-value Int 1 vs. Con > 0.05 In 2 vs. Con > 0.05	No clear change (1.4% and 8.1% decrease at intervention sites; 7.4% decrease at control sites)
	NO_x	Mean change Int 1 = −7.5 Int 2 = −7.7 Con = −6.1	p-value Int 1 vs. Con > 0.05 In 2 vs. Con > 0.05	No clear change (9.2% and 16.1% decrease at intervention sites; 15.9% decrease at control sites)
	NO_2	Mean change Int 1 = −1.5 Int 2 = −3.4 Con = −4.5	p-value Int 1 vs. Con < 0.05 In 2 vs. Con > 0.05	Significant increase when comparing change at streetside intervention sites (3.2% decrease) to change at control sites (17.4% decrease)
Intervention 17 Burr 2004	RSP effects	Net improvement = −6.5	95% CI = (−14.9; 2.0)	No clear change
Intervention 18 Carrillo 2013 Even-odd restriction	CO	DiDiD estimator = −0.0890	p-value < 0.001	Significant 9% decrease
Intervention 19 Cowie 2012 Tunnel construction; Road restructuring	PM_{10}	Adj mean change = −0.67	p-value > 0.05	No clear change (3.8% decrease)
	$PM_{2.5}$	Adj mean change = 0.17	p-value > 0.05	No clear change (2.9% increase)
	NO_x	Adj mean change = −2.06	p-value > 0.05	No clear change (8.1% decrease
Intervention 20 Dijkema 2008 Speed limit change	PM_{10}	Adj mean change Int = −2.20 Con = −0.97	95% CI Int = (−2.98; −1.43) Con = (−1.68; −0.25)	Significant decrease when comparing change at intervention sites (7.4% decrease) to change at control sites (3.5% decrease)
	BS	Adj mean change Int = −3.57 Con = −2.43	95% CI Int = (−5.65; −1.50) Con = (−3.80; −1.05)	No clear change (15.0% decrease at intervention sites; 12.1% decrease at control sites)
	NO_x	Adj mean change Int = −2.13 Con = −1.87	95% CI Int = (−7.25; 3.00) Con = (−5.68; 1.94)	No clear change (2.4% decrease at intervention sites; 2.7% decrease at control sites)
Intervention 21 Dolislager 1997 Fuel requirements	CO	% change = −8.0	NR	Significant 8.0 decrease
Intervention 22 El-Zein 2007 Diesel vehicle ban	RSP hospital (immediate)	Regression coefficient = −0.165	p-value = 0.04	Significant decrease
	RSP hospital (long-term)	Regression coefficient = 0.128	p-value = 0.32	No clear change

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Table 5 (*continued*)

Study	Outcome	Effect estimate	Reported measure of variability or statistical significance	Narrative description
Intervention 23 Fensterer 2014 Low emission zone	PM_{10}	Adj % change = −13.0	p-value < 0.001	Significant 13% decrease
Intervention 24 Davis 2008/Gallego 2013a Even-odd restriction	NO_x	Adj % change = 17.3	NR	Significant 17.3% increase
	NO_2	Adj % change = 8.9	NR	Significant 8.9% increase
	SO_2	Adj % change = −9.2	NR	No clear change (9.2% decrease)
	O_3	Adj % change = 28.0	NR	Significant 28% increase
	CO (immediate)	Adj % change = −13.0	p-value < 0.05	Significant 13% decrease
	CO (long-term)	Adj % change = 11.3	p-value = 0.12	Unclear change (11.3% increase)
Intervention 25 Gallego 2013b/ Gramsch 2013 Public transport restructuring	BC	% change Int = 4.8 Con = 17.4	p-value Int = 0.028 Con < 0.01	No clear change (4.8% increase at intervention sites; 17.4% increase at control sites)
	CO (immediate)	% change = −5.9	p-value > 0.1	No clear change (5.9% decrease)
	CO (long-term)	% change = 26.8	p-value < 0.01	Significant 26.8 increase
Intervention 26 Hasunuma 2014 Required vehicle standards	RSP effects	Mean change Int = −0.59 Con = −0.13	95% CI Int = (−0.88; −0.31) Con = (−0.46; 0.20)	Significant 17.4% decrease at intervention sites, no clear change (3.5% decrease) at control sites
	NO_x	Mean change Int = −6.04 Con = −3.20	95% CI Int = (−7.10; −4.99) Con = (−4.42; 1.98)	Significant 22.5% decrease at intervention sites, no clear change (21.6% decrease) at control sites
Intervention 27 Kim 2011 Clean fuel use	PM_{10}	% change Int = 14.7 Con = −4.7	p-value Int = 0.01 Con = 0.6	Significant 14.7% increase at intervention sites, no clear change (4.7% decrease) at control sites
	NO_2	% change Int = −1.13 Con 1.0	p-value Int = 0.78 Con = 0.35	No clear change (1.13% decrease at intervention sites; 1.0% increase at control sites)
Intervention 28 Morfeld 2014 Low emission zone	NO_x	Adj mean change = −1.74	95% CI = (−2.2334; −1.145)	Significant 3.5% decrease
	NO_2	Adj mean change = −1.12	95% CI = (−1.137; −0.087)	Significant 2.2% decrease
	NO	Adj mean change = −1.128	95% CI = (−1.555; −0.702)	Significant 2.3% decrease
Intervention 29 Peel 2010 Comprehensive traffic reduction strategy	CV hospital	Adj relative risk = 0.996	95% CI = (0.829; 1.195)	No clear change (0.4% decrease in risk)
	PM_{10}	% change Int = −17.0 Con 1 = –33 Con 2 = −10.1	p-value Int = 0.239 Con 1 = 0.432 Con 2 = 0.479	No clear change (concentrations decreased at intervention and control sites)
	NO_2	% change Int 1 = −11.0 Int 2 = −13.8 Con 1 = −1.0 Con 2 = −14.3 Con 3 = −7.7	p-value Int 1 = 0.450 Int 2 = 0.397 Con 1 = 1.0 Con 2 = 0.367 Con 3 = 0.523	No clear change (concentrations decreased slightly at intervention and control sites)
	SO_2	% change Int 1 = 8.0 Int 2 = 36.6 Con 1 = −57.4 Con 2 = −25.6 Con 3 = 19.7	p-value Int 1 = 0.941 Int 2 = 0.613 Con 1 = 0.185 Con 2 = 0.662 Con 3 = 0.885	No clear change (concentrations increased at control sites, increased and decreased at control sites)
	O_3	% change Int 1 = −30.0 Int 2 = –33.0 Con 1 = −27.0 Con 2 = −29.4 Con 3 = −16.8 Con 4 = −25.0 Con 5 = −37.1 Con 6 = −18.4 Con 7 = −16.7 Con 8 = −18.4	p-value Int 1 < 0.001 Int 2 < 0.001 Con 1 < 0.001 Con 2 = 0.004 Con 3 = 0.001 Con 4 < 0.001 Con 5 < 0.001 Con 6 = 0.114 Con 7 = 0.034 Con 8 = 0.035	No clear change (concentrations decreased at intervention and control sites)
	CO	% change Int = −45.8 Con 1 = −21.4 Con 2 = –22.7 Con 3 = −0.9 Con 4 = 6.5	p-value Int = 0.053 Con 1 = 0.355 Con 2 = 0.466 Con 3 = 0.999 Con 4 = 0.867	No clear change (concentrations decrease across most intervention and control sites)
	RSP hospital	Adj relative risk = 1.012	95% CI = (0.920; 1.113)	No clear change (1.2% increase in risk)
Intervention 30 Ruprecht 2009 Charging scheme	PM_{10}	Pre-post ratio Int = 0.9517 Con = 0.9504	NR	No clear change (similar decreases at intervention and control sites)
Intervention 31 Titos 2015a Road restructuring	NO_x	% change Int = −72.0 Con = 6.0	p-value Int < 0.01 Con > 0.05	Significant 72% decrease at intervention sites, no clear change (6% increase) at control sites
Intervention 32 Titos 2015b Public transport restructuring	SO_2	% change Int = −37.0 Con = −14.0	p-value Int < 0.01 Con > 0.05	Significant 37% decrease at intervention sites, no clear change (14% decrease) at control sites

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Table 5 (*continued*)

Study	Outcome	Effect estimate	Reported measure of variability or statistical significance	Narrative description
Intervention 33 Viard 2015 Even-odd restriction	PM_{10} (Even-odd policy)	Adj % change = −31.0	p-value < 0.01	Significant 31% decrease
	PM_{10} (One-day policy)	Adj % change = −27.0	p-value < 0.01	Significant 27% decrease
Intervention 34 Yorifuji 2016	AC mortality	Adj % change = −2.1	95% CI = (−2.8; −1.4)	Significant 2.1% decrease in risk
	CV mortality	Adj % change = −5.9	95% CI = (−7.2; −4.6)	Significant 5.9% decrease in risk
	RSP mortality	Adj % change = −10.0	95% CI = (−12; −8.1)	Significant 10.0% decrease in risk
Required vehicle standards				

Abbreviations: all-cause (AC); cardiovascular (CV); respiratory (RSP); triple difference-in-differences (DiDiD); adjusted (Adj); intervention (Int); control (Con).

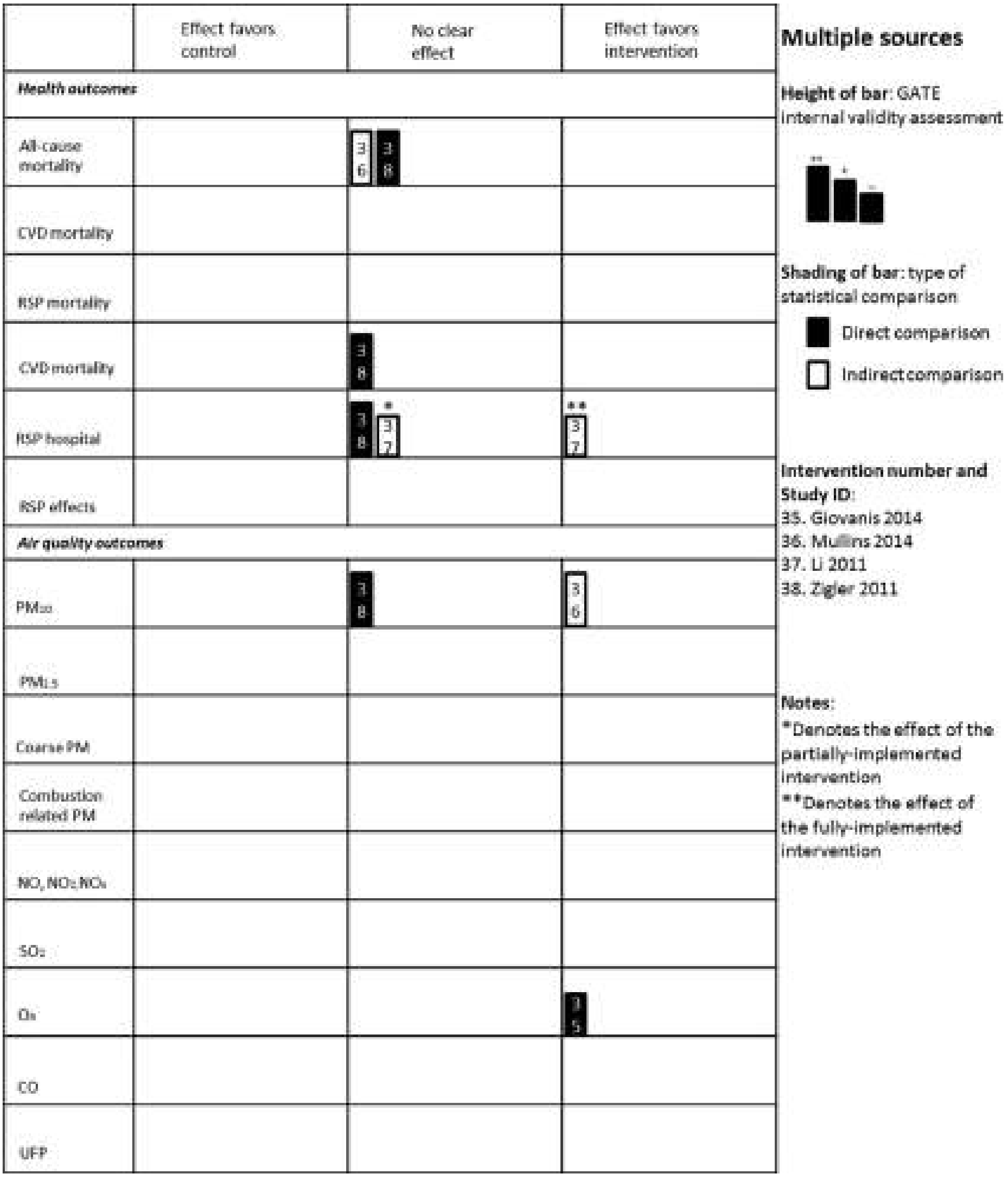

Fig. 7. Harvest plots summarizing effects of interventions targeting multiple sources on health (top panel) and air quality (bottom panel) outcomes.

Two studies evaluated legislation aiming to reduce air pollution. Dolislager (1997) (Intervention 21) observed a significant decrease in CO concentrations associated with fuel standards in California restricting the oxygen content of gasoline in winter months. Hasunuma et al. (2014) (Intervention 26) observed a significant decrease in NO_2 concentrations associated with the NOx/PM Law which introduced the designation of “enforcement areas” and associated vehicle standards in Japan.

4.3.4. Multiple interventions vs practice as usual

For the evidence synthesis of interventions to reduce ambient air pollution from multiple sources, three studies contributed evidence on health outcomes and three studies contributed evidence on air quality outcomes. As illustrated in Fig. 7, observed associations between interventions and both health (top panel) and air quality (bottom panel) outcomes were mixed, with all studies showing either no clear association or a significant association in favor of the intervention. The reported effect estimates as well as reported data on uncertainty and/or statistical significance can be found in Table 6.

With regard to health outcomes, Mullins and Bharadwaj (2014) (Intervention 36) observed no clear change in all-cause mortality associated with coordinated measures to reduce vehicular and industrial pollution enacted in Santiago, Chile on days for which poor air quality is forecast. Li et al. (2011) (Intervention 37) initially observed no clear change in respiratory hospitalizations when the intervention was only partially implemented, and subsequently observed a significant decrease associated with the full set of measures aiming to decrease vehicular and industrial pollution during the 2008 Beijing Olympic Games. Zigler et al. (2016) (Intervention 38) observed no clear change in all-cause mortality, cardiovascular hospitalizations or respiratory hospitalizations associated with the US National Ambient Air Quality Standards non-attainment designation, given as part of the US Clean Air Act to areas which did not meet the air quality standards.

With regard to air quality outcomes, Giovanis (2014) (Intervention 35) observed a significant decrease on O_3 concentrations associated with coordinated measures to reduce vehicular and industrial pollution enacted in Charlotte, North Carolina, USA on days for which poor air quality is forecast. Mullins and Bharadwaj (2014) (Intervention 36) observed a significant decrease in PM_{10} concentrations associated with coordinated measures to reduce vehicular and industrial pollution enacted in Santiago, Chile on days for which poor air quality is forecast. Zigler et al. (2016) (Intervention 38) observed no clear change in PM_{10} concentrations associated with non-attainment designation given as part of the US Clean Air Act to areas not meeting the National Ambient Air Quality Standards.

5. Discussion

5.1. Summary and discussion of main results

This is the first systematic review to assess the effectiveness of interventions in reducing pollutant concentrations and improving associated health outcomes. Given the heterogeneity across interventions, outcomes, and study methods, it was not possible to derive any overall conclusions regarding the effectiveness of specific interventions in improving air quality or health, nor were we able to highlight specific types of interventions likely to be most effective. Most interventions, whether aiming to reduce pollution from industrial, residential, vehicular or multiple sources, observed either no significant association in either direction or an association favoring the intervention. There is very little evidence suggesting that any of the assessed interventions were harmful.

In interpreting these results, however, it is important to consider several factors that may have impacted individual study results. Establishing a causal relationship between individual air pollution interventions and changes in air quality and health outcomes is

Table 6
Reported effect estimates from studies assessing interventions targeting multiple sources.

Study	Outcome	Effect estimate	Reported measure of variability or statistical significance	Narrative description
Intervention 35	O_3	DiD estimator = −1.268	p-value < 0.01	Significant 2.3% reduction
Giovanis 2014				
Repeated coordinated measures				
Intervention 36	AC mortality	DiD estimator = −3.611	p-value > 0.05	No clear change (5.6% decrease)
Mullins 2014	PM_{10}	DiD estimator = −22.53	p-value < 0.01	Significant 22.53% decrease
Repeated coordinated measures				
Intervention 37	RSP hospital (partial implementation)	Adj relative risk = 1.24	95% CI = (0.93; 1.76)	No clear change (24% increase in risk)
Li 2011	RSP hospital (full implementation)	Adj relative risk = 0.50	95% CI = (0.47; 0.55)	Significant 50% reduction in risk
Even-odd restriction; Vehicle restriction; Power plant restriction				
Intervention 38	AC mortality	Causal estimate = −1.08	95% posterior interval = (−3.27; 0.99)	No clear change (1.08 fewer deaths per 1000 person years)
Zigler 2016	CVD hospital	Causal estimate = 1.44	95% posterior interval = (−4.64; 6.16)	No clear change (1.44 additional hospitalizations per 1000 person years)
Tailored selection of measures				
	RSP hospital	Causal estimate = 1.44	95% posterior interval = (−4.64; 6.16)	No clear change (1.44 additional hospitalizations per 1000 person years)
	PM_{10}	Causal estimate = −1.47	95% posterior interval = (−3.86; 0.70)	No clear change (1.47 fewer hospitalizations per 1000 person years)

Abbreviations: all-cause (AC); cardiovascular (CV); respiratory (RSP); difference-in-differences (DiD); adjusted (Adj); intervention.

challenging for a range of reasons. First, the nature of the causal pathway between a specific air pollution intervention and changes in health, as illustrated by the HEI chain of accountability (HEI, 2003), is long and complex. The introduction of an intervention must first lead to reductions in source emissions, followed by reduced ambient pollutant concentrations, reduced exposure/dose for the individual, and finally improvements in health; all of these steps in the chain may also be influenced by the broader environmental and social context in which an intervention is embedded.

Second, these interventions do not exist in a vacuum, and often multiple interventions are implemented within the same time frame, and at multiple levels (e.g., local, regional, and national) in the context of a host of other long-term environmental and societal changes. Large-scale regulatory programs have likely been effective in improving air quality (Correia et al., 2013; Gilliland et al., 2017; Schindler et al., 2009); determining whether individual interventions within such programs are effective, however, is particularly challenging. They may be implemented in multiple separate steps, and may not have immediate effects on either air quality or health. Also, the biological processes that underlie adverse health effects of air pollution may take years to manifest, and are also associated with a complex array of genetic, biological, social, cultural and environmental factors (Dahlgreen and Whithead, 1991; Graham and White, 2016). Such interventions are evaluated against the backdrop of long-term trends of demographic change (i.e. population growth, increasing life expectancies and ageing), changes in healthcare practice and coverage, industrialization and economic development, which likely lead to increased motorized vehicle traffic, more potentially polluting industries and greater energy use for lighting, cooking, heating and various electric appliances in residences.

Third, as previously discussed, ambient air pollution represents a complex mix of pollutants, originating from a range of sources, with approximately 15% of urban ambient pollution stemming from industrial sources, 20% from residential sources and 25% from vehicular sources (Karagulian et al., 2015). Thus, interventions aiming to reduce air pollution from a single source inherently only address part of the problem, and air pollution from other sources, including industrial, residential and vehicular sources, but also agricultural and other transport-related sources such as shipping and flight traffic likely affect air quality and health. This has implications both for researchers trying to evaluate interventions and decision-makers implementing interventions. For evaluations, where an intervention addresses only one of multiple sources, changes in overall concentrations or health outcomes may be difficult to detect, especially where monitoring efforts are not sufficiently extensive or poorly placed to measure population exposures. With regard to policy, this suggests that efforts to improve air quality and health are likely to require a systems approach that targets multiple sources through a combination of different measures in a context-and setting-specific manner (Rutter et al., 2017). A recent assessment focusing on national policy recommendations in the German context also supported this conclusion (Leopoldina, 2019).

All of these aspects contribute to the challenge of firstly, improving ambient air quality and health outcomes through specific interventions, and secondly, detecting these changes through rigorous research methods. These aspects should, therefore, be considered when interpreting effects from individual studies, including those described in this review. The determination of causality for relationships is based on a cumulative evidence approach, drawing on various lines of evidence including epidemiology, animal toxicology and human clinical studies (Dominici and Zigler, 2017; Owens et al., 2017). Accountability studies are a valuable addition to that evidence base, but they represent only one piece of the puzzle.

5.2. Strengths and limitations of the systematic review

Throughout the conduct of the review, from the initial scoping stages to the interpretation and reporting of the evidence, we applied systematic, robust and transparent methods according to Cochrane standards. We defined our review question and the exact parameters based on a system-based logic model (Rehfuess et al., 2017; Rohwer et al., 2017). We conducted multi-disciplinary and multi-database electronic searches, and attempted to locate non-published literature. Our protocol was reviewed by a RAG consisting of air pollution researchers as well as decision makers who represent the potential end-users of this review. In order to better reflect the reality of the air pollution research field, we included a wide range of study designs, including the study designs normally included in EPOC reviews (Cochrane EPOC, 2017), but also non-EPOC CBA studies. We summarized the heterogeneous evidence base narratively, but also created harvest plots with the aim of more effectively communicating the evidence. We reviewed the certainty of the overall body of evidence using the GRADE system, recognizing that reported concerns regarding the application of this approach to public health interventions (Rehfuess and Akl, 2013) or interventions characterized by complexity (Montgomery et al., 2019) also apply in this review (Burns et al., 2019). All of these methodological aspects were helpful in ensuring that the results reported here are valid, relevant and understandable.

There were, however, challenges in the review conduct, and some decisions we made may have led to the introduction of bias into the systematic review. We also introduced several changes after publication of the protocol, all based solely on methodological considerations and independent of study results. A complete discussion of these changes and potential biases in the review process can be found in the full review; here we provide only a brief summary.

Decisions surrounding inclusion of studies were sometimes challenging. For example, the classification of included studies into one of our included study designs was challenging, and it is possible that potentially eligible studies were misclassified. Additionally, determining whether interventions were designed to or could potentially improve ambient air quality was not always straightforward. Allen et al. (2009) and Aung et al. (2016), for example, both of which primarily aimed to improve indoor air quality, met all inclusion criteria. These studies, however, may not have been designed or implemented to improve ambient air quality at the population-level. We aimed to be inclusive at the screening stage and discussed any uncertainties at the full text screening stage among at least three review authors to avoid such exclusion.

As described in the methods, the final date of searches was August 2016, thus the most current studies are not included in this review. Our RAG identified several studies published since then that would potentially be included in the review (Barreca et al., 2017; Font and Fuller, 2016; Gehrsitz, 2017; Hales et al.; Han et al., 2018; Li et al., 2017; Yinon and Thurston, 2017). This list of studies is very likely non-comprehensive. However, based on an informal examination of the additional studies identified, it does not appear that the conclusions of this review would be altered. It is clear that this represents a very active field of study, and that an update of this review will be beneficial in the near future.

We did not include studies that have taken an indirect approach, such as cohort studies, to assessing the effects of interventions. Such studies have been conducted in Switzerland (Schindler et al., 2009), California (Gauderman et al., 2015; Gilliland et al., 2017), the entire US (Correia et al., 2013; Dominici et al., 2007; Pope et al., 2009), and the Netherlands (Boogaard et al., 2013), among others. Put simply, these studies show that decreases in pollutant concentrations, observed over time periods when interventions were implemented, were associated with improvements in health outcomes. Another important type of studies, excluded from this review, are those in which participants self-select into lower exposure areas, such as in the ‘Movers study’ (Avol et al., 2001). Additionally, we excluded modeling studies, where concentration-response functions from existing epidemiological studies are applied to predict health outcomes from measured or modelled changes in air quality. This was done in the evaluation of the LEZ in Rome (Cesaroni et al., 2012). Inclusion of these additional study types may have influenced the results and interpretations of the review.

The potential influence of publication bias should not be ignored, as it is possible that some studies, particularly those not finding any effect or those potentially observing harmful effects of interventions, have not been published. As protocols or analysis plans of non-randomized studies are typically not registered in this research field, it is difficult to judge whether all planned analyses were conducted and reported. Of the 42 main studies, only 3 cited a study protocol or described study registration (Aung et al., 2016; Morfeld et al., 2013, 2014).

We defined interventions based on four categories, thus there are certain types of interventions not covered by this review, and an alternative categorization placing less emphasis on the emission source may have yielded a different evidence base. Measures of personal protection, including masks and filtration systems were not included. Additionally, we did not include studies assessing changes to agricultural practices. In fact, these aspects were also not considered by several other non-systematic reviews (Bell et al., 2011; Boogaard et al., 2017; Henneman et al., 2017; Henschel et al., 2012; Rich, 2017). Two recent reviews applying rapid assessment approaches focusing on the UK and German context include agricultural interventions (Leopoldina, 2019; PHE, 2019), and one assessment focused on face mask interventions in the French context (ANSES, 2018).

5.3. Recommendations for research and practice

We identified few or no studies from several parts of the world, including Africa, the Middle East, Eastern Europe, Central Asia and Southeast Asia. Thus there is a need to strengthen the evidence base by evaluating existing and future interventions.

To ensure a better future understanding of 'what works', it is important that decision-makers help ensure high-quality evaluations. Such high-quality evaluations undertaken in different settings and countries should ideally follow an internationally agreed evaluation framework that encourages a more systematic assessment and facilitates comparisons across studies. Air pollution interventions, and especially long-term regulatory programs, would benefit from having an evaluation component built into them from the start (Boogaard et al., 2017). Such a system of contemporaneous evaluation would also require a system for reliable tracking of both air quality and health outcomes data over the long-term, including quality assurance of the data and making them publicly available (Boogaard et al., 2017). Concomitant and potentially more in-depth evaluations could also comprise process evaluations, providing important insights into the fidelity, feasibility, quality of implementation and causal mechanisms related to interventions and their effects for different population groups (Moore et al., 2015).

Researchers should also focus on improving the internal validity of future evaluations. Studies assessing interventions aiming to reduce ambient air pollution are, like other epidemiological studies, susceptible to confounding, and the choices surrounding study design and analysis methods are critical. It is particularly important that future evaluations focus on the use of appropriate comparison populations or outcomes (i.e. negative controls) unaffected by the intervention, and account for underlying background trends in outcomes. The development of new statistical frameworks and techniques for controlling for confounding could also contribute to more appropriate evaluations (Boogaard et al., 2017). Researchers should also clearly consider and communicate their hypotheses and assumptions regarding expected improvements and study power, i.e. expected changes in pollutant concentrations, underlying susceptibility of populations, expected response in health, and whether the assessed data are sensitive enough to detect these effects.

Future studies should also focus on complete and detailed reporting of all study aspects. Reporting guidelines, such as the CONSORT statement for randomized studies (Schulz et al., 2010), the STROBE statement for observational studies (Vandenbroucke et al., 2007) and the TREND statement for non-randomized evaluations (Des Jarlais et al., 2004), are a good starting point, but even these may not be sufficient. Where possible, authors should go beyond describing these aspects in a brief overview. Resources exist to facilitate better description of the intervention (Campbell et al., 2018; Hoffmann et al., 2014), and of context and implementation (Pfadenhauer et al., 2017). In reporting results authors should provide effect estimates, as well as some measure of variance, such as the 95% confidence interval. Similarly, the publication or registration of study protocols or analysis plans would help to protect against selective reporting.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2019.105400.

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