UK Health Security Agency

Chemical Hazards and Poisons Report
Issue 28 – June 2022

Reducing health harms associated with air pollution

Contents

Foreword

Many thanks to all involved in the preparation of this excellent, comprehensive, and informative report, which I am confident will prove useful and helpful to our many and diverse partners and stakeholders across government, academia, campaign groups, and the voluntary sector in the battle for clean, healthy air.

As we emerge from what we all hope is the worst of the coronavirus (COVID-19) pandemic, this is perhaps a good opportunity also to reflect on the lessons for reducing health harms arising from air pollution. At both national and global level, air pollution presents a health challenge broadly similar in scope and scale to that of COVID in terms of annual mortality and morbidity. Yet air quality does not dominate our nightly news, our behavioural choices, and our political discourse in anything like the same way. Sadly, air pollution remains for most of us the 'silent killer', invisible, with its effects often only being felt years after exposure, when action is too late. Health impacts of air pollution often lack the immediacy of the dramatic short-term spikes in illness and death that we recall all too vividly during the pandemic, or that our parents and grandparents remember during the 'pea souper' smogs of the 1950s.

For this reason, it is all too easy to forget or ignore the insidious effect that air pollution has on our, and our children's future health. The measures needed to improve air quality require bold thinking and a commitment to act locally and nationally: cleaner transport, energy generation, and industry, or restrictions on where we can drive or on the fuels we burn. Local initiatives all too often run into opposition and delays. Industrial activities that generate pollution are largely out of sight and out of mind. We spend roughly 90% of our lives indoors, yet we are largely oblivious to the cocktail of pollutants released within our homes or drawn in from the outdoor environment.

UKHSA and our partners remain absolutely committed to delivering healthier futures through cleaner air, backed up by legislation and long-term commitment on the part of government. To succeed, this must be based on strong, incontrovertible scientific evidence, which needs to be communicated in a clear, useful, informative, and accessible way, and which can be used by individuals and policymakers in order to make informed decisions and to take appropriate action. I hope that this report goes at least some way to delivering exactly that.

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Background

Breathing in polluted air affects our health, reduces our life expectancy and it costs the NHS and our society billions of pounds each year (1). Evidence continues to build showing that even low concentrations of air pollution can cause a variety of health effects throughout our lifetime, it is a significant public health burden. Improving air quality needs to be a priority as small reductions in concentrations of air pollution could prevent thousands of respiratory and cardiovascular diseases, lung cancer and other health effects over the next 2 decades (2).

Exposure to harmful air pollution doesn't just occur in the outdoor world. As people spend increasing amount of their time indoors (3), the indoor environment plays a key role on the health and wellbeing of everyone. The health impacts of these indoor air pollutants can trigger or exacerbate asthma, irritation of the eyes, nose, and throat, and other respiratory or cardiovascular conditions; they may even have carcinogenic effects. It is estimated that over 2 million healthy life years are lost in the Europe due to the impacts of poor indoor air quality (4).

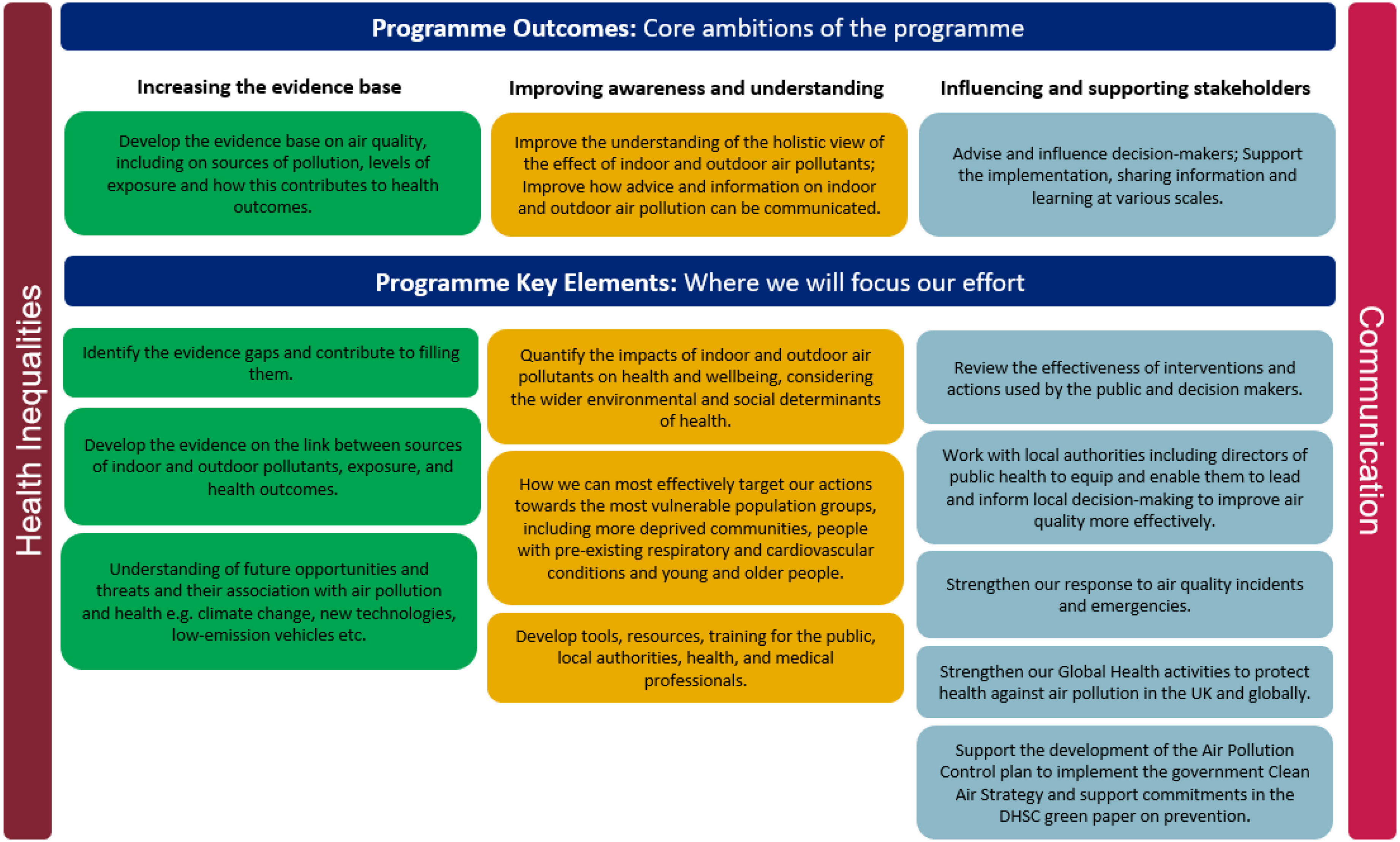
The UKHSA Cleaner Air Programme

Despite improvements in the air quality in England over the previous decades, it remains the highest environmental risk factor; therefore, it remains important to make the case for action to address air pollution. A programme of work, originally established by the Air Quality and Public Health (AQPH) group in Public Health England (PHE), following consultation with a wide range of stakeholders, aims to reduce people's exposure to air pollution, achieve better outcomes for all – particularly for the most vulnerable groups such as those with pre-existing respiratory and cardiovascular conditions, older people, pregnant women and children – and deliver physical and mental health as well as climate change co-benefits. It is organised around 3 core outcomes that describe the breadth of UKHSA's day-to-day work towards helping people in England enjoy cleaner air and healthier lives wherever they live. Figure 1 lists these: increasing the evidence base, influencing, and supporting stakeholders, and improving awareness and understanding.

Figure 1. Core outcomes of the UKHSA's Cleaner Air Programme

To help achieve the 3 core outcomes of the programme, 11 key programme elements (Figure 2) describe specific programmes that focus effort across UKHSA towards these strategic goals. These were selected based on their alignment with the UKHSA mission, considering the advice of internal and external experts and best available evidence of where action can achieve the largest benefits for public health.

Figure 2. Key Elements of the UKHSA Cleaner Air Programme



Accessible text version of Figure 2. Key Elements of the UKHSA Cleaner Air Programme

Cross-cutting themes: health inequalities, communication

Programme Outcomes: Core ambitions of the programme

1. Increasing the evidence base

Develop the evidence base on air quality, including on sources of pollution, levels of exposure and how this contributes to health outcomes.

2. Improving awareness and understanding

Improve the understanding of the holistic view of the effect of indoor and outdoor air pollutants; Improve how advice and information on indoor and outdoor air pollution can be communicated.

3. Influencing and supporting stakeholders

Advise and influence decision-makers; Support the implementation, sharing information and learning at various scales.

Programme Key Elements: Where we will focus our effort

1. Increasing the evidence base

Identify the evidence gaps and contribute to filling them.

Develop the evidence on the link between sources of indoor and outdoor pollutants, exposure, and health outcomes.

Understanding of future opportunities and threats and their association with air pollution and health, such as climate change, new technologies, low-emission vehicles and so on.

2. Improving awareness and understanding

Quantify the impacts of indoor and outdoor air pollutants on health and wellbeing, considering the wider environmental and social determinants of health.

How we can most effectively target our actions towards the most vulnerable population groups, including more deprived communities, people with pre-existing respiratory and cardiovascular conditions and young and older people.

Develop tools, resources, training for the public, local authorities, health, and medical professionals.

3. Influencing and supporting stakeholders

Review the effectiveness of interventions and actions used by the public and decision makers.

Work with local authorities including directors of public health to equip and enable them to lead and inform local decision-making to improve air quality more effectively.

Strengthen our response to air quality incidents and emergencies.

Strengthen our Global Health activities to protect health against air pollution in the UK and globally.

Support the development of the Air Pollution Control plan to implement the government Clean Air Strategy and support commitments in the DHSC green paper on prevention.

Two cross-cutting themes of communication and health inequalities underpin the programme. To maximise the impacts of each project, how it will be communicated to its audience is considered from the outset and UKHSA is committed to ensuring stakeholders are fully involved. We know that the health impacts of air pollution are unequally distributed amongst different population groups. By embedding consideration of air pollution's potential to disproportionately affect certain groups in every piece of work we undertake, we aim to ensure that the improved health outcomes are equally shared.

The following chapters of this report highlight some of the successes, under the 3 core outcomes of the Cleaner Air Programme since it was established in March 2020, including work with our stakeholders and collaborators.

Next steps

Reducing health harms from air pollution continues to be a high priority for the UKHSA, and the organisation is fully committed to the existing Cleaner Air Programme. The AQPH team has a unique role sitting at the interface between academia and policy, where it is well positioned to achieve the long term aims of the programme: increasing evidence and ensuring that policy makers are using the best possible evidence, improving awareness, and understanding and encouraging behavioural change at all levels, and influencing and supporting stakeholders to take action to reduce the burden of health of air pollution and address health inequalities.

We are currently planning our 'Annual UK Review Meeting on Outdoor and Indoor Air Pollution Research' and 'Air Quality and Public Health Stakeholder Seminar' for later in the year where we can share the latest evidence, hear from leading researchers in the field, see examples of best practise and discuss how we can all work together to help reduce the health harms from air pollution.

Acknowledgements

The authors would like to thank all the AQPH group, past and present, staff from the Environmental Hazards and Emergencies Department and other departments in the Radiation, Chemical and Environmental Hazards Directorate, others across the agency and all our stakeholders who are integral to the programme's previous and future successes. The authors would particularly like to thank Eleanor Sykes for her invaluable contribution to the development of the Cleaner Air Programme.

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Theme 1: Building the evidence-base

We work to build and develop the evidence base on air quality, publishing publications, journals, reports, and policy briefs on a range of topics. These include work on the sources of air pollution both indoors and outdoors (such as transport, solid fuel burning and composting), levels of exposure (including specific contexts, such as at schools) and socioeconomic differences and how they contribute to health outcomes (such as dementia, respiratory effects, and mental health) as well as reviewing the effectiveness of interventions (such as the use of indoor air purifiers). Publication case studies are outlined below (see Appendix for a full list of papers).

Air quality around schools: Part I – A comprehensive literature review across high-income countries (1)
Children can encounter pollution peaks on the school journey, at school gates, and in school playgrounds. Nearby traffic is a key determinant of concentrations outside schools; and factors relating to planning and urban design – such as the type of playground paving and amount of surrounding green space – can influence school site pollutant concentrations. The authors suggested that more personal monitoring to better understand exposure around schools and that 'before and after' evaluation of local interventions is needed. studies Recommendations for policymakers included the creation of clean air zones around schools; greening of school grounds; careful selection of new school sites and promotion of active travel to and from school.

Air quality around schools: Part II – Mapping $PM_{2.5}$ concentrations and inequality analysis (2)
Modelled annual mean concentrations at school locations indicated that over a third of schools in England were in areas where annual mean $PM_{2.5}$ in 2017 exceeded the World Health Organization recommended guideline (10 μgm^{-3}). Schools in areas with high annual mean $PM_{2.5}$ levels (>12 μgm^{-3}) had a significantly higher median intake of pupils on free school meals compared to schools in low $PM_{2.5}$ areas. Schools in the highest $PM_{2.5}$ concentration range were more likely to be ethnically diverse, near major roads and less likely to be near significant green space.

Portable air purification: Review of impacts on indoor air quality and health (3)
The evidence indicated that using portable air purifiers results in short-term reductions in $PM_{2.5}$ in the indoor environment with reductions varying between 22.6 and 92%. This may offer health benefits but there were limited studies which had also investigated the associated health improvements and the results were inconsistent.

Exposure to indoor air pollution across socio-economic groups in high-income countries (4)

Inequalities in indoor exposures may relate to poor quality housing, a lack of education regarding the harms of indoor second-hand smoke, higher occupant density, locations near congested roads resulting in greater re-suspension of particles. Significant additional research is required to examine inequalities in indoor exposures. Modelling approaches may provide opportunities to quantify exposure disparities due to housing and behaviours across populations of different socio-economic status.

Assessing the exposure to air pollution during transport in urban areas – evidence review (5)

This evidence review found that higher concentrations of air pollutants were often experienced in motorised transport compared to cycling and walking. However, closing car windows and operating ventilation in recirculation mode was found to lower particulate pollution concentrations inside cars. Pedestrians and cyclists were generally exposed to lower concentrations of air pollution when using routes separated from motorised traffic; the exposure of cyclists could be over 3 times higher when cycling on a high-traffic route compared to cycling on a traffic-free route and over 4 times higher when comparing cycling on-carriageway with cycling on a separated cycle lane.

As part of its work to develop the evidence base on air quality, the UKHSA works with a range of stakeholders including expert committees, working parties and academics.

The UKHSA AQPH team provides the scientific secretariat for the Committee on the Medical Effects of Air Pollutants (COMEAP). COMEAP provides independent advice to government departments and agencies on how air pollution impacts on health. Recently, it has produced advice on health effects from non-exhaust particulate matter from road transport (6) and recommendations for quantifying the effects of air pollution (7), quantifying hospital admissions associated with short-term exposures (8) and quantifying mortality associated with long-term exposure to fine particulate matter (9). Based on COMEAP's advice UKHSA has updated mortality burden estimates attributable to air pollution.

We've contributed to the publication of the Royal College of Paediatrics and Child Health's (RCPCH) 'The inside story: Health effects of indoor air quality on children and young people' (10). This report includes the findings from a systematic review of the effects of indoor air quality on children's health. The report makes recommendations, originating from both experts and young people, addressing risks to children's health from indoor air quality. We've also worked with the World Health Organization (WHO) to develop a 'Screening questionnaire for selection of sampling sites for assessment of risks from combined exposure to multiple chemicals in indoor air' (11).

During the coronavirus (COVID-19) pandemic, UKHSA alongside COMEAP undertook evidence reviews and provided ad-hoc advice to government departments and agencies on the evidence on COVID-19 and air pollution (addressed in more detail in the feature article at the end of this issue). UKHSA also supported work by the Office of National Statistics to assess evidence of any association between exposure to air pollution and COVID-19 mortality in the UK (12)

UKHSA has partnered with universities affiliated with National Institute of Health Research (NIHR) Health Protection Research Units (HPRUs). These units act as centres of excellence in multidisciplinary health protection research in England and are described in more detail in 2 articles in this issue.

We also have active partnerships with universities and other research organisations, with UKHSA staff represented on UK Research and Innovation funded networks on indoor/outdoor air either as co-investigators or on in advisory capacities (addressed in more detail in the concluding article in this section).

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Updated mortality burden estimates attributable to air pollution

Estimates using new COMEAP recommendations for quantification

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Abstract

An estimate of the mortality burden attributable to long-term exposure to air pollution is useful in communications about the public health significance of air pollution.

The Committee on the Medical Effects of Air Pollutants (COMEAP)[1] recently updated its recommendation for quantification of mortality associated with long-term exposure to fine particle air pollution ($PM_{2.5}$) (1). The recommended concentration-response function (CRF[2]) is 1.08 (95% CI: 1.06, 1.09) per 10μg/m^3 annual average $PM_{2.5}$. The use of a cut-off value is not recommended when quantifying the mortality burden and thus quantification can be carried out down to very low $PM_{2.5}$ concentrations by assuming a log-linear shape for the CRF.

We applied the method developed by COMEAP (2) to estimate the mortality burden associated with long-term exposure to air pollution using the updated CRF. Using this approach, the mortality burden associated with exposure to the air pollution was estimated for the UK and separately for the 4 constituent nations. The new estimates suggest that the burden of long-term exposure to air pollution in 2019 in the UK was an effect equivalent to 29,000 to 43,000 deaths for adults aged 30 and over.

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[1] Committee on the Medical Effects of Air Pollutants. The scientific secretariat of the committee is provided by the Air Quality and Public Health (AQPH) group of the UK Health Security Agency (UKHSA)

[2] An increase of 10μg/m3 in population-weighted annual average background concentration of $PM_{2.5}$ is assumed to increase all-cause mortality rates by a unit relative risk (RR) factor of 1.08

Introduction

In its 2010 report 'The mortality effects of long-term exposure to particulate air pollution in the United Kingdom', COMEAP included an estimate of the mortality burden of existing levels of particulate air pollution on the population of the UK: an effect on mortality in 2008 equivalent to 29,000 deaths (3). Nitrogen dioxide (NO_2) also contributes to the health burden of air pollution, and in 2018, COMEAP published a report on the 'Associations of long-term average concentrations of nitrogen dioxide with mortality' (2). As well as providing advice to Defra on how to estimate the mortality benefits of reducing long-term average concentrations of NO_2, the report proposed an exploratory method to estimate the mortality burden of long-term exposure to air pollution. The method used associations of mortality reported with both fine particle air pollution ($PM_{2.5}$) and NO_2 (as discussed below). The range of central estimates of the UK mortality burden in 2013 associated with these pollutants was an effect equivalent to 28,000 to 36,000 deaths, at ages at which deaths typically occur.

Recently, COMEAP updated its recommendations for quantification of mortality associated with long-term exposure to $PM_{2.5}$ (1). The changes in the quantification method include:

- a new coefficient of the concentration-response function (CRF) of 1.08 (95% CI: 1.06, 1.09) per 10µg/m^3 annual average $PM_{2.5}$ based on a summary effects estimate from a meta-analysis by Chen and Hoek (4) of the available global literature (previous coefficient: 1.06 (95% CI: 1.04, 1.08) (5))
- the use of total, rather than only the anthropogenic, fraction of $PM_{2.5}$ in burden estimates

As explained by COMEAP (1), the previous use of the anthropogenic fraction of particulate pollution was because anthropogenic particulate matter can be considered as the theoretical maximum that could potentially be influenced by policy interventions. However, the concentration of $PM_{2.5}$ corresponding to zero anthropogenic pollution is not straightforwardly defined in practice, as concentrations of $PM_{2.5}$ derived from sources that might initially be considered 'natural' are also affected by anthropogenic activities. For example, both resuspended dust particles and biogenic volatile organic compounds (precursors of secondary organic aerosol) are influenced by the cultivation of crops. Also, recent assessments from the Pollution Climate Mapping (PCM) model[3] showed that the contribution of sea salt to UK population-weighted annual mean $PM_{2.5}$ in 2018 and 2019 is of the order of 0.5μg/m^3. Epidemiological studies are continuing to find human health effects down to very low concentrations. Thus, the use of a cut-off value is not recommended for quantification, but it is recommended to extrapolate to zero (or low values based on levels reported in epidemiological studies) $PM_{2.5}$ using an assumption of continuing log-linearity.

UKHSA has updated the mortality burden estimates by following the method described by COMEAP (2), adapted to reflect the new COMEAP recommendations for quantifying the $PM_{2.5}$ associated mortality. In the COMEAP report (2), scientific and methodological challenges in understanding the extent of the independence of the associations of mortality with concentrations of NO_2 and $PM_{2.5}$ were identified and discussed. According to this report, the recommended quantification method should include the use of unadjusted and adjusted coefficients for assessing the mortality burden of air pollution in the UK based on long-term average concentrations of NO_2 and $PM_{2.5}$.

Methods – data

The method described by COMEAP (2) allows quantification using either $PM_{2.5}$ or NO_2 as the primary indicator of the air pollution, and using unadjusted coefficients to capture, as fully as possible, the effect of the air pollution as a whole via single-pollutant analyses. The results of single-pollutant estimates in $PM_{2.5}$ and in NO_2 should not be added together, because this would lead to overestimation of the effects of the air pollution. Instead, it is advised to use the higher of the 2 estimates. Also, a combination of paired reductions of the summary coefficients from single pollutant models for both NO_2 and $PM_{2.5}$ is recommended to be used for producing mutually adjusted coefficients. Pairs of coefficients from 4 studies (6 to 9) were selected, and for each study, the percentage reduction in NO_2 coefficient on adjustment for $PM_{2.5}$ is applied to the unadjusted summary NO_2 coefficient; similarly, the percentage reduction in $PM_{2.5}$ coefficient on adjustment for NO_2 is applied to the unadjusted summary $PM_{2.5}$ coefficient. The estimated burdens obtained using these mutually adjusted summary coefficients are then summed to give an estimated burden of the air pollution.

Estimates obtained in this way can be compared with those derived using unadjusted coefficients for NO_2 and $PM_{2.5}$. More explanation on the use of unadjusted and adjusted

[3] The Pollution Climate Mapping (PCM) model is an air pollution model that is calibrated using data from monitoring data at background sites in Defra's Automatic Urban and Rural Network (AURN). The PCM model simulated the annual average $PM_{2.5}$ concentrations used by COMEAP (2, 3) as the basis of its burden estimates

coefficients for NO_2 and $PM_{2.5}$, and the reasons for following this approach to estimate the mortality burden attributable to air pollution, are provided in the COMEAP report (2).

In regard to associations with NO_2, COMEAP has recommended the use of an unadjusted coefficient of 1.023 (95% CI: 1.008, 1.037) per 10µg/m^3 annual average NO_2 for the assessment of the mortality benefits of interventions that reduce traffic-related pollutants (2).

The percentage reductions, and adjusted summary coefficients, used in the calculations are presented in Table 1.

Table 1. Coefficients for use in mortality attributable to NO_2 and $PM_{2.5}$ burden calculations

Indicator pollutant	**Unadjusted coefficients***	**Various options for adjusted coefficients (NO₂ adjusted for PM2.5 and vice versa, derived as paired NO₂ and PM2.5 % reductions from unadjusted to adjusted coefficients from each study)**			
		Jerrett et al (6)	**Fischer et al (PM_{10}) (7)**	**Beelen et al (8)**	**Crouse et al (with O_3) (9)**
NO_2 single pollutant model summary estimate (first column) and summary estimate reduced by the relevant % reductions from each study (reduction on adjusting single pollutant coefficient)	1.023**	1.019 (19%)	1.016 (29%)	1.011 (53%)	1.020 (13%)
$PM_{2.5}$ single pollutant model summary estimate (first column) and summary estimate reduced by the relevant % reductions from each study (reduction on adjusting single pollutant coefficient)	1.08**	1.037 (53%)	1.042 (46%)	1.069 (14%)	1.025 (68%)

*NO_2: Chapter 2 of COMEAP (2]; $PM_{2.5}$: COMEAP (1) and Chen and Hoek (4)

**The percentage reductions corresponding to the confidence intervals around the central estimates of the coefficients are not estimated due to various difficulties explained in COMEAP (2018a) Working Paper 3 (2)

The data required for the mortality burden estimates includes the population-weighted concentrations (Table 2) and the all-cause mortality data for adults aged at least 30 years (Table 3) for the UK and each nation separately in 2019.

Table 2. Population-weighted mean NO_2 and $PM_{2.5}$ concentrations in 2019 (μg/m³)

Country	Population (number of people)	Population-weighted annual mean concentration (μg/m³)	
		NO_2	$PM_{2.5}$
England	55,986,500	15.1	9.6
Wales	3,130,402	9.3	7.5
Scotland	5,436,871	9.6	5.5
Northern Ireland	1,881,623	8.4	5.9
UK	66,435,396	14.2	9.0

Source: Ricardo and UK-air

Table 3. All-cause mortality in 2019 (number of deaths)

Country	All-cause mortality (number of deaths)	
	All ages	age 30+
England	496,370	489,447
Wales	33,183	30,315
Scotland	58,108	57,314
Northern Ireland	15,758	15,441
UK	604,707	596,185

Sources: Northern Ireland Statistics and Research Agency (NISRA), National Records Scotland (NRS), Office for National Statistics (ONS)

Results

The numbers of deaths attributable to long-term exposure to air pollution per country and in the UK in 2019 are presented inTable 4.

In the UK, using single-pollutant models for NO_2 or $PM_{2.5}$ as indicators of the air pollution gave estimates of 19,000 and 40,000 respectively; the 2 estimates should not be added together, but the higher of these should be used, as this is likely to underestimate the burden the least. By using the pairs of adjusted coefficients from the 4 different studies, the values range from 29,000 to 43,000. This encompasses the estimate based on the use of the single pollutant model for $PM_{2.5}$ and represents the burden of long-term exposure to air pollution.

Separately in the 4 nations, the attributable deaths ranges were:

- England, 26,000 to 38,000
- Wales, 1,200 to 2,000
- Scotland, 1,800 to 2,700
- Northern Ireland, 470 to 730

Table 4. Mortality attributable to long-term exposure to the air pollution per country in 2019

Country	Attributable mortality by using unadjusted coefficients		Attributable mortality by combining pairs of adjusted coefficients			
	NO_2 unadjusted coefficient	$PM_{2.5}$ unadjusted coefficient	Jerrett et al (6)	Fischer et al (7) (PM_{10})	Beelen et al (8)	Crouse et al (9) (with O_3)
England	16,498	34,767	30,449	30,275	38,102	25,735
Wales	712	1911	1,507	1,522	1,996	1,240
Scotland	1,235	2,382	2,162	2,136	2,655	1,845
Northern Ireland	290	685	568	569	732	474
UK	18,735	39,745	34,687	34,503	43,485	29,295

Conclusions – discussion

The key conclusions of this analysis are summarised as:

- by applying the new methods to 2019 air pollutant concentrations, a larger mortality burden estimate (29,000 to 43,000) than in the 2018 COMEAP report (2) (28,000 to 36,000 based on data from 2013) was produced for the UK
- the highest numbers of attributable deaths amongst the UK countries are estimated for the most populous country England, where they range from 26,000 to 38,000

In comparison to the previously published estimates by COMEAP (2), the new mortality burden estimates are higher, although the air pollutant concentrations in 2019 are similar to, or even lower than, 2013 (population-weighted annual mean concentrations in the UK in a. 2013: NO_2: 17.4µg/m^3 and anthropogenic $PM_{2.5}$: 8.9µg/m^3, b. 2019: NO_2: 14.2µg/m^3 and $PM_{2.5}$: 9.0µg/m^3) and the numbers of deaths are also similar across the 2 years. Thus, this difference in the estimates is largely because recent evidence suggests a greater effect on mortality than it did previously.

It should be noted that the annual number of 'attributable deaths' associated with long-term average concentrations of pollutants is not an estimate of the number of people whose untimely death is caused entirely by air pollution. Instead, it is a way of representing the effect of air pollution across the whole population: air pollution is considered to act as a contributory factor to many more individual deaths. Therefore, it is recommended to use expressions such as, an effect equivalent to a specific number of deaths at typical ages" for the burden estimates (1). In COMEAP's report (2), the mortality burden was provided in terms of life years lost as well (328,000 to 416,000); although it is not calculated here, this metric is recommended to be used as it includes information on the age of population and survival rates considering the air pollution exposure.

A number of scientific and methodological challenges were identified by COMEAP (2) in interpreting the extent of the independence of the associations of mortality with concentrations of NO_2 and $PM_{2.5}$. These include the different amounts of exposure misclassification[4] of each pollutant, the 'transfer of effect' which may occur when 2 pollutants are highly correlated and where one is measured or modelled with more error than the other, and other statistical issues.

The method we followed is accompanied by a series of uncertainties, as outlined below. Firstly, the modelling of ambient $PM_{2.5}$ concentrations is subject to uncertainty associated with emission inventory estimates and various model components. Secondly, variations in toxicity between the various components of $PM_{2.5}$ was not considered; according to COMEAP there is insufficient evidence to provide a quantitative comment on the risk arising from different components of suspended particles (1). Thirdly, a factor of uncertainty arises from the heterogeneity in associations reported in the available epidemiological studies. This heterogeneity is likely due to various factors, such as differences in methodology and exposure assessments, concentration of air pollutants, composition of $PM_{2.5}$, population, geographic location, and time period. In addition, given the correlation between particle concentrations and other pollutants, uncertainty relates to attribution of causality to exposure to particulate matter and other components of the air pollution.

In this analysis, data from 2019 rather than 2020 or 2021 was used; the mortality data of the more recent years would reflect effects of the COVID-19 pandemic and also the air pollutants' concentrations during the lockdown periods might not represent long-term concentrations (10).

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[4] Exposure misclassification refers to differences between the exposure metrics used in the epidemiological study and the 'true' exposures of the population at risk

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Air quality research in the National Institute of Health Research funded Health Protection Research Units

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Background

The National Institute of Health Research (NIHR) Health Protection Research Units (HPRUs) are research partnerships between universities and the UK Health Security Agency. The units act as centres of excellence in multidisciplinary health protection research in England. There are 15 HPRUs with total available funding of £58.7 million (over the current five-year period 1 April 2020 to 31 March 2025), amounting to about £4 million per HPRU. In addition to novel translational research, the HPRUs are charged with undertaking training, Patient and Public Engagement, Interaction and Participation and Knowledge Mobilization.

The overall aim of the HPRUs is to provide high quality scientific translational evidence to support UKHSA in implementing effective public health interventions to reduce the burden of ill health. To achieve this, projects are mainly directly translation-knowledge-generating, and many are relatively short duration. As well as contributing to the research, UKHSA works to steer the research priorities and translate the research into practice. The research outcomes are circulated by various means including research publications, workshops, direct interaction with practitioners and support to government expert committees (such as the Committee on Medical Effects of Air Pollutants (COMEAP) and Committee on Toxicity (COT)). In this way the research underpins advice, policy, and practice. Furthermore, the HPRUs are charged with enhancing the UK economy through improving public health and wellbeing, as well as through working with industry to develop new products and services informed by health protection research. HPRU funding, therefore, adds significant value to the outputs, relative to the funding available from NIHR.

Health Protection Research Units (HPRUs)

During the previous round of HPRU funding from 2014 to 2020, a HPRU in 'Health impacts of Environmental Hazards' (HIEH) mainly focussed its research on air quality, spanning from in vitro laboratory studies right through to epidemiology studies. From 2020, 4 new HPRUs were funded that focus on environmental hazards, see Table 1.

Table 1. HPRUs focussing on environmental hazards

HPRU name	Summary
Environmental Exposures and Health (EEH) HPRU at Imperial College, London	The aims of the EEH HPRU are: i) identification of existing and emerging environmental hazards, ii) quantification of risk to human individuals and populations utilizing assessment of hazard and exposure, iii) further the understanding of causal biochemical pathways and toxic properties of environmental contaminants and development of in vitro models, iv) identification of the populations and individuals at greatest risk so that interventions (including prevention policies and treatments) can be appropriately targeted and v) response to emerging issues
Environmental Exposures and Health HPRU at University of Leicester	The University of Leicester, in partnership with UKHSA and Health and Safety Executive, focuses on the health effects of exposures in the built environment. The HPRU research is currently investigating 5 project areas examining the effect on health of indoor air, bioaerosols, soil and dust contaminants, water contaminants and environmental noise
Environmental Change and Health (ECH) HPRU at London School of Hygiene and Tropical Medicine	The ECH HPRU provides research to support decision-making relating to the impacts of climate change and other environmental changes that affect human health. Its current programme of research has 10 pre-defined research topics, and its work on the adaptation of housing to climate change and health impacts is particularly relevant to air quality
Chemical and Radiation Threats and Hazards (CRTH) HPRU at Imperial College, London	The mission of the CRTH HPRU is to undertake research on the health effects of exposures to hazardous chemicals and radiation to improve their assessment, management, and control. The main aim is to gain new knowledge on the distribution, determinants, mechanisms, and pathways linking these exposures to health effects and to advance understanding of how the everyday and exceptional contact that the public has with chemicals and radiation leads to ill health

The original HIEH HPRU became the HPRU in Environmental Exposures and Health (EEH). This HPRU was initially funded at £4 million and envisaged to be one unit. However, in the final round due to the strength of the applications (into which UKHSA had substantial input and leadership) an additional £1 million was provided by the NIHR and 2 EEH applications were funded, resulting in one being held at Imperial College London and the second (called a development HPRU and funded at £1 million) at the University of Leicester. The HPRU in Environmental Change and Health is a continuation from its previous HPRU and is in association with the London School of Hygiene and Tropical Medicine, Kings College London, and the Met Office.

Key air pollution research questions being addressed

The HPRUs are undertaking to help answer some of the most important questions around air pollution and health to guide policy-related action. Examples of their research are included in the following sections.

How does air pollution affect our health?

The effect of exposure to air pollution on the life-course is important area of continued study. Adverse birth outcomes have been associated with air pollution exposure (1) and this will be investigated further by Imperial at the request of the Committee on the Medical Effects of Air Pollutants (COMEAP).

An emerging area of interest is the association between air pollution and mental health, research has suggested that traffic-related air pollution may affect mental health (2) and that residential air pollution exposure is associated with increased mental health service use (3). In addition to better-understood drivers of behavioural problems in adolescence, such as racism and broader inequalities, there is emerging evidence of the impacts of exposure to air pollution on adolescent behaviour (4).

Cognitive decline is also an area of past HIEH HPRU research where a potential link between cognitive decline and exposure to air pollution was found (5, 6). The link between dementia and exposure to particulate matter in the air has been taken forward for further analysis in the current workplan (7).

Mechanistic work is planned by Imperial EEH HPRU to look at causal pathways, for example, in relation to asthma, and between different air pollutants such as nitrogen dioxides and particulates. The latter are difficult to distinguish epidemiologically due to co-variance having many of the same sources.

How does exposure to air pollution vary in different environments?

A key source of exposure to air pollution is via transport. Previous ECH HPRU work examined occupational and public exposures to air pollution from nitrogen monoxide and nitrogen dioxide in the transport sector (8).

Exposure to the transport microenvironment and diesel exhaust fumes had been shown to have effects at the molecular level (9), so this was an area to take forward into the Imperial EEH HPRU. Recent reviews looking at the occupational exposure of drivers have been published examining interventions (10, 11, 12), and biomarkers following exposures to particles at airports have also been examined (13).

Exposure studies are planned in transport locations to examine systemic and respiratory physiologic and biochemical endpoints by the Imperial EEH HPRU. In these same environments, epidemiological studies will be carried out to examine correlations between occupational exposures and sickness absence. Biomarkers from exposure to diesel and biodiesel exhaust and woodsmoke will be identified, as well as biomarkers from smoking and vaping cohorts. Chemical characterisation of brake and tyre particulate matter will be investigated and particles from metal-to-metal contact on underground trains.

Future work in the CRTH HPRU focuses on biomarkers of exposure, effect, and susceptibility to chemical exposures in new housing developments built on brownfield sites, many of which are in inner city areas with high air pollution levels. A project is also planned to investigate possible pollutants and their exposures among the population living near selected closed landfill sites and waste composting sites.

How can we improve our understanding of indoor air quality?

Work is underway in the Leicester EEH HPRU to improve methods to identify and quantify volatile organic compounds in homes. This will support a case-control study of people with severe asthma to compare indoor air exposures to moulds, volatile organic compounds (VOCs) and carbon monoxide (CO) in patients' homes and relate these to their symptoms. A current project examining the effect of VOCs released from fragranced products on indoor air quality is featured in this issue.

Other research areas include CO exposures, as previous studies investigated health burdens and suggested associations between hospital admissions and CO poisoning (14). A paper has recently been submitted by the Leicester EEH HPRU that characterises CO exposure measurement errors in current epidemiology approaches and potential improvements in these methods for future studies (15). This will enable academic institutions and policy bodies to have a better understanding of the true burden on CO exposure and health risks on the population. Research has identified CO poisoning continues to cause fatalities and that there is a clear need for measures that raise awareness of the dangers of CO poisoning, especially amongst men working alone in garages or outbuildings (16). Additionally, there is a lack of knowledge of the impacts of lower levels of CO exposure, and this understanding is critical for accurate disease burden estimates.

To extend work on the impacts of (building-related) climate change mitigation and adaptation measures on housing, further work by the ECH HPRU is focussing on critical alterations in ventilation parameters and range of effects on health arising from unintended changes to indoor air quality.

What can we do to reduce exposure?

Considering new sources of exposure to air pollution is important, and researchers at Leicester University and HSE are characterising Volatile Organic Compounds (VOCs) and particle emissions from 3D printers. This will inform consideration of appropriate control measures and guidance on safe use to minimise exposure risks for users of the printers and inform good practice and guidance for the education sector and the public.

Researchers are helping to understand how bioaerosols affect our health to improve advice to healthcare professionals and people with asthma. Here, the 2 HPRUs in Environmental Exposures and Health are working together to maximise impact. Current projects are advancing understanding of potential bioaerosol exposure from composting facilities (17) and fungal seasons (18). UKHSA colleagues discuss the public health implications of bioaerosols in more detail in an article in this issue.

Interventions in the housing sector are of particular interest for the ECH HPRU, specifically those that improve home energy-efficiency. Energy-efficiency can be achieved through reducing ventilation losses and lowering air exchange, which protects against ingress of pollutants from the outdoor environment but can increase indoor pollutants such as radon, VOCs, and mould (19 to 21). The HPRU also continues to research transport-related interventions to reduce air pollution exposures (22). It is considering related factors such as climate change and health co-benefits associated with interventions that aim to improve air quality, such as pedestrianisation and reduced vehicle speed limits, as well as implications for vulnerable populations and places associated with high exposure.

Reactive work: COVID-19 and air pollution

The HPRUs are expected to assist with emerging issues. When the coronavirus (COVID-19) pandemic began, scientists from the HPRUs contributed to evidence generation, interpretation, and advice to government. The following sections highlight some of the key questions and publications.

How did air quality change during the lockdown?

Lockdown meant that there was less traffic on the roads, and scientists investigated how big a difference this made to air pollution levels. The data was complicated to interpret but essentially large decreases in nitrogen dioxide concentrations were seen, together with small changes in fine particulate matter concentrations and increases in ozone concentrations. Related publications:

- examined changes in air quality during COVID-19 'lockdown' in the United Kingdom (23)
- contributed to the evidence call for Defra's report 'Estimation of changes in air pollution emissions, concentrations and exposure during the COVID-19 outbreak in the UK' (24)

What makes a good study design to investigate COVID-19 and air pollution?

At the start of the pandemic, there was a rush of research papers published before peer review stating effects of air pollution on COVID-19 related mortality. Not all were scientifically rigorous. HPRU scientists provided expert advice to help steer future research and interpret the evidence in the following publications:

- 'Expert input on methods used in ecological analyses for Office for National Statistics (ONS) COVID-19 related mortality rates and the effects of air pollution in England' (25)
- 'Responding to COVID-19 requires strong epidemiological evidence of environmental and societal determining factors' (26)
- 'Research Challenges and Public Health Implications' (27)

Is there an association between air pollution and COVID-19?

An important question was whether living in areas with high pollution made people more likely to get COVID-19 or whether air pollution might make health effects more severe. Initial advice was that while there was no clear evidence, it was considered possible that exposure to air pollutants could increase the likelihood or severity of COVID-19 infection. A detailed review of current evidence investigating the association between air pollution and COVID-19 is included in the concluding feature article of this issue. Related publications include:

- 'COMEAP's ongoing work air pollution and COVID-19' (28)
- 'COVID-19: what role might air pollution play?' (29)
- 'Expert reaction to study looking at air pollution and COVID-19 deaths' (30)
- 'Investigating the links between air pollution, COVID-19 and lower respiratory infectious diseases' (31)
- 'Household Air Pollution and Respiratory Symptoms a Month Before and During the Stringent COVID-19 Lockdown Levels 5 and 4 in South Africa' (32)

Find out more

The HPRUs are keen to work with a range of stakeholders throughout their current and future research on air quality and health. More details can be found online or by contacting the Knowledge Mobilisation leads:

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  - Environmental Exposures and Health – NIHR
  - The NIHR Health Protection Research Unit in Environmental Change and Health | LSHTM

- Chemical Radiation Threats and Hazards – NIHR

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Characterising the indoor environment in residential buildings: the effect of fragranced products

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Introduction

The University of Leicester, in partnership with the UK Health Security Agency (UKHSA) and Health and Safety Executive (HSE), started a five-year National Institute for Health Research (NIHR) funded Health Protection Research Unit (HPRU) development award in Environmental Exposures and Health in 2020, with a focus on the health effects of exposures in the built environment. The HPRU research focuses on 5 project areas examining the effect on health of indoor air, bioaerosols, soil and dust contaminants, water contaminants and environmental noise. The vision of the HPRU is to conduct high quality, multidisciplinary, applied research, which can be readily translated into public and workforce health policy and clinical practice. Researchers within the HPRU are developing new technologies and methods to improve exposure assessment and will combine this with laboratory studies, epidemiological analyses, and health impact assessments to support the evidence base for policy and clinical practice. Public involvement panels and knowledge mobilisation are being used to increase involvement of stakeholders, communities and community groups in the research and outputs. This article showcases a current project examining the effect of fragranced products on indoor air quality.

The effect of fragranced products on indoor air quality and health

Nowadays, people spend 90% of their times indoors (1). This time spent in public and residential buildings, like their home, workplace, or school, can lead to long-term exposure to poor air quality with the potential to impact their health. The sources of this exposure are diverse and multiple, and sometimes originate from products used on a daily basis. Studies are beginning to look at the impact of these exposures on human health.

Consumer products are one of the main sources of indoor air pollution and these products release a variety of Volatile Organic Compounds (VOCs) into the indoor environment. A study characterised the VOCs emitted by 37 common consumer products (such as air fresheners, cleaners, laundry products, and personal care products). Fragranced products were determined to emit the highest number of VOCs: 144 different VOCs including 35 classified as toxic or hazardous under US federal laws. The most common VOCs released by fragranced products are D-limonene and α-pinene (2), both of which are included in the UKHSA Indoor Air Quality Guidelines for selected VOCs due to concern about their risk to human health the in the indoor environment (3).

Studies examining the impact of fragranced consumer products on human health have shown that within the general population 23.9% of people surveyed reported adverse health effects (such as respiratory problems, mucosal symptoms, and migraine headaches) after exposure to fragranced products compared to 55.6% of asthmatics. Among these asthmatics, 24% reported an asthma attack induced by exposure (4).

Characterising indoor concentrations of VOCs from fragranced products

In a study of 25 homes conducted in the UK, D-Limonene and α-pinene were the most commonly detected VOCs measured within indoor air, present in 94% of the houses tested (5). In one of the houses described in this study, the mean five-day concentration of D-limonene was measured at 807μgm^{-3}. The occupant of this house used 9 different fragranced products more than 10 times per week, which may explain the high concentration measured. Although this level is under the limit value proposed by UKHSA Indoor Air Quality Guidelines, set at 9000μgm^{-3} for a day (3).

A pilot study of VOC exposure in 4 homes has been performed by the team at the University of Leicester HPRU. In this study, VOCs present in the different rooms of the studied houses were identified and quantified at different times throughout the day. D-limonene and α-pinene were also the most abundant VOCs detected in the houses studied. The highest mean D-limonene concentration measured was 42 μgm^{-3}, averaged over 15 hours. The concentration of D-limonene and α-pinene changed dramatically during the day depending on the occupants' activities. Figure 1 shows that in one of the houses studied, the D-limonene concentration was 50 times higher during the preparation of the evening meal compared to in the morning.

Figure 1. Evolution of D-limonene concentration during 15 hours

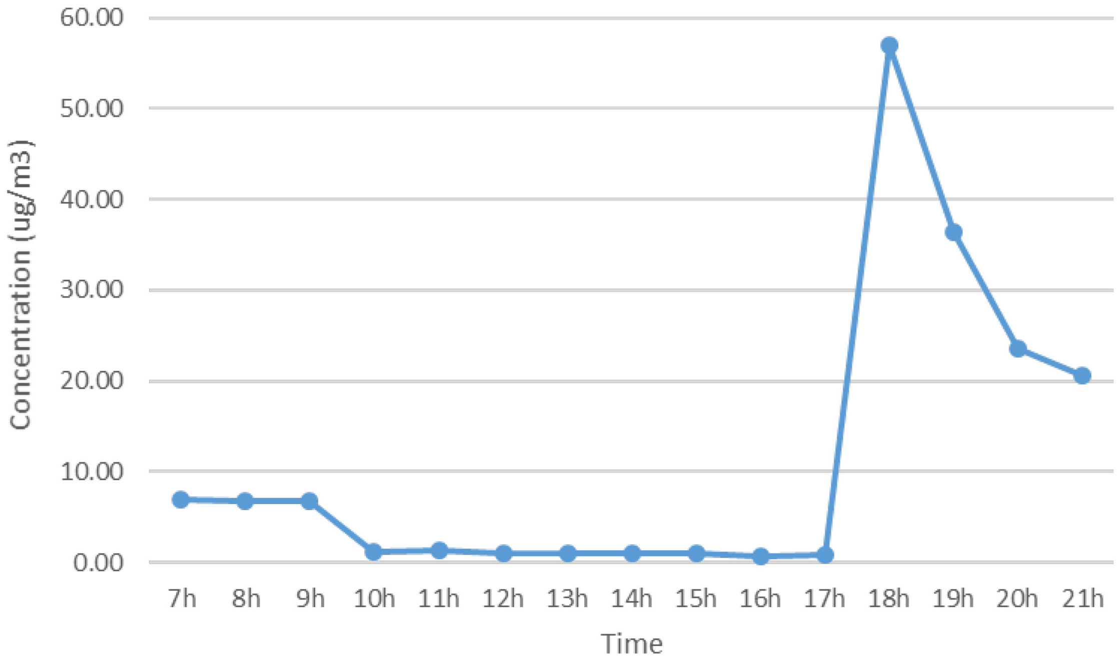

Figure 1: Evolution of D-limonene concentration during 15 hours

This variability was also observed between days: Figure 2 shows that in one studied house, the mean concentration of D-limonene during the first sampling day (41.53µgm^{-3}) was 3.5 times higher than on the second day of sampling (12.60µgm^{-3}). This increase of the ambient concentration can be explained by the delivery of an order of fragranced personal care products.

Figure 2. Evolution of D-limonene concentration between 2 days

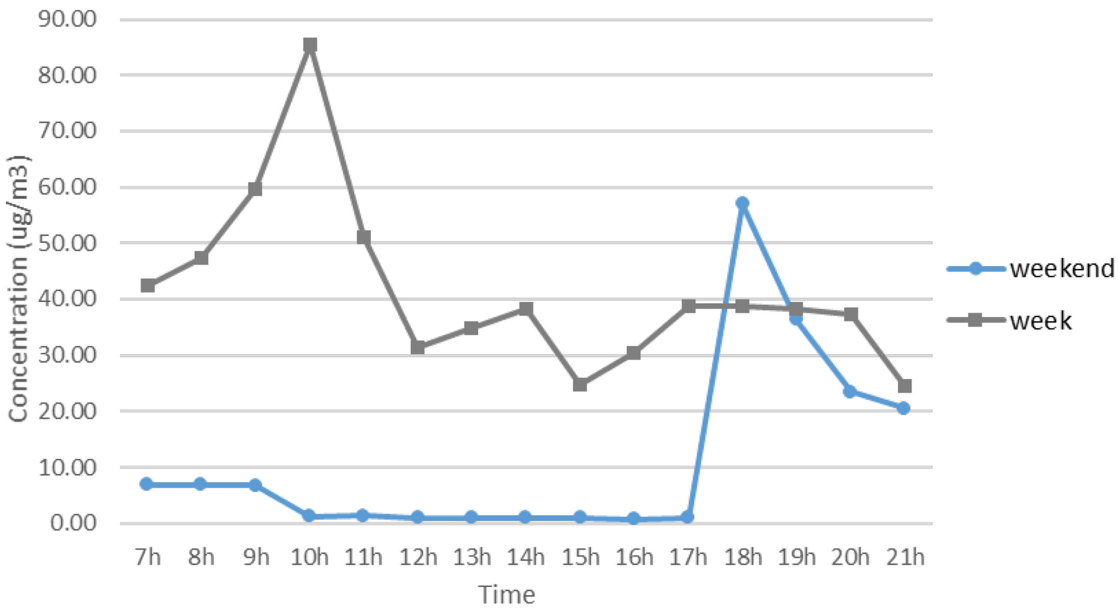

Figure 2: Comparison of D-limonene concentration between two days

After using fragranced products, the concentration of D-limonene decreases in the following hours. Two hours after reaching the highest concentration, the concentration reduced by an average of half in the houses studied. Similar results were obtained in a chamber test ventilated at approximately 0.5l/h (6). In addition to losses via ventilation another D-limonene can also react in indoor air with ozone, another pollutant present in the home, to create formaldehyde (7). The presence of a high concentration of D-limonene (891μgm^{-3}) on contact with 100μgm^{-3} of ozone can induce the production of 41μgm^{-3} of formaldehyde (8).

Formaldehyde is a ubiquitous VOC generally present in the home at a concentration between 15-30μgm^{-3} (9). This VOC is known to impact human health, causing various health effects depending on its concentration and time of exposure. Formaldehyde obtained from D-limonene and α-pinene can lead to sensory irritation in the upper airway (10). According to UKHSA Indoor Air Quality Guidelines, short-term exposures can cause eye, nose, and throat irritation, coughing and dyspnoea, and long-term exposure is associated with nasal cancer. UKHSA Indoor Air Quality Guidelines has fixed the short-term exposure limit value at 100 μgm^{-3} for 30 minutes, and the long-term limit value at 10 μgm^{-3} for a year (3).

Research into practice: public health interventions and advice

Studies to date suggest that fragranced products can have an immediate impact on human health. The lifestyle of the occupants and the products used are some of the major factors that can affect the concentration of these VOCs indoors. The National Institute for health and Care Excellence (NICE) published in 2020 a guideline on improving indoor air quality (11). Various advice was given depending on the target audience. One of them related to use of these products, suggesting that persons with breathing problems who report symptoms after using this type of products should either avoid using them or find an alternative. For example, opening windows rather than using a fragranced air freshener. Another option to reduce VOCs emissions in the indoor environment is the use of fragrance-free products.

Future work

The pilot study conducted by the University of Leicester HPRU's team has been extended to several homes in the East Midlands area and a more detailed chemical characterisation of the indoor air environment of these homes is being performed, including measurements of the D-limonene, α-pinene, formaldehyde and ozone concentrations. The next phase of the study will involve recruitment of patients with moderate to severe asthma, who might be expected to be most sensitive to respiratory irritants. Indoor VOC exposures, respiratory symptoms and lung function will be monitored over several weeks and statistical analyses will determine if there are clear short-term relationships.

The University of Leicester HPRU's team is also studying several other sources of VOC emissions, including a PhD studentship working with the Health and Safety Executive (HSE) on the characterisation of VOCs emitted by newer 3D printers and their potential impact on human health. This work will help fill in some of the many gaps related to knowledge about VOC exposures in indoor air in the UK and potential to identify modifiable health risks.

More details on the HPRU and its projects can be found at the Leicester HPRU website.

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Understanding the public health implications of bioaerosols

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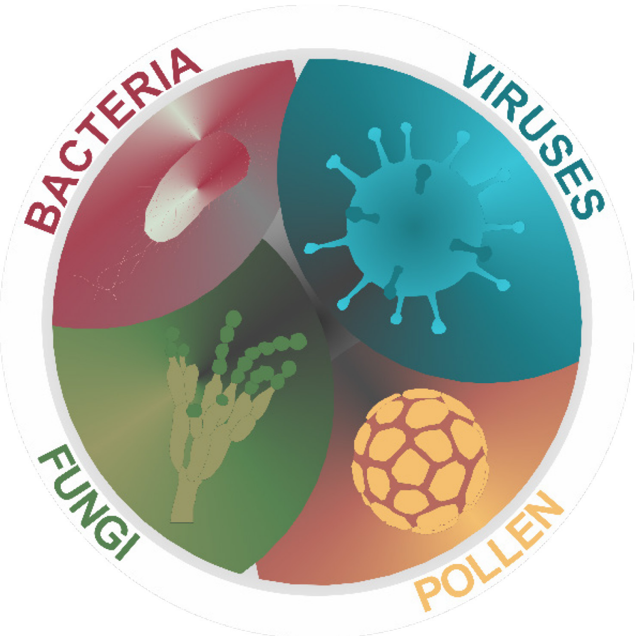
What are bioaerosols?

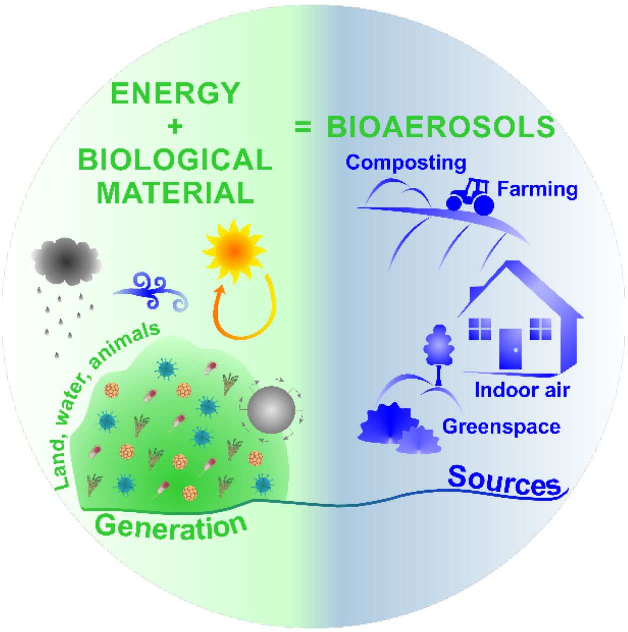
The air we breathe, as well as containing the main gases oxygen, nitrogen, and carbon dioxide, contains billions of airborne particles both organic and inorganic in origin. Some of these airborne particles contain organisms either live, dormant, or dead, such as fungi, bacteria and viruses, or parts of organisms, such as dusts, toxins, and plant pollen (Figure 1). These airborne biological particles are termed 'bioaerosols' (1 to 3). Bioaerosols are naturally found in the environment and are common in the air we breathe.

Figure 1. The consistuents of bioaerosols



Bioaerosols are present both indoors and outdoors and can be generated by a number of natural and human processes (Figure 2). They are formed when small particles are separated from larger biological materials. These particles are not often visible to the naked eye and can range in size from around 0.02 to 100μm in diameter, either existing as single cells or particles, or clumping together to form aggregates (4).

Figure 2. Bioaerosol generation



Where do they come from and how are we exposed?

Bioaerosols are made up of naturally occurring biological material from a range of sources (Figure 2). For example, the mechanisms by which fungi and plants spread spores and pollen are designed to allow these particles to be taken by air currents as far and wide as possible (2). However, bioaerosols can also be generated from human activities such as waste management and industrial farming. Processes such as composting, anaerobic digestion, mechanical biological treatment and agricultural practices can produce bioaerosols. The spread and behaviour of bioaerosols depend on the physical properties of the particles in the bioaerosol and the environmental conditions that they encounter (1).

Individuals can be exposed to a number of different bioaerosols throughout the day depending on the different environments they are moving through at home, at work or during recreational activities.

Outdoor bioaerosols will likely contain pollen; agricultural dusts; fungi, bacteria and their associated products from soil and vegetation; and viruses. The time of year can affect the composition and levels of bioaerosols present in the air. For example, in late summer and early autumn, peaks of up to 50,000 fungal spores/m^3 can be detected, and pollen concentration increases over the summer months as plants produce flowers (5). Weather can also impact bioaerosol composition and concentrations, with wind, temperature, humidity, rainfall, and thunderstorms influencing the release and dispersal of fungal spores (6).

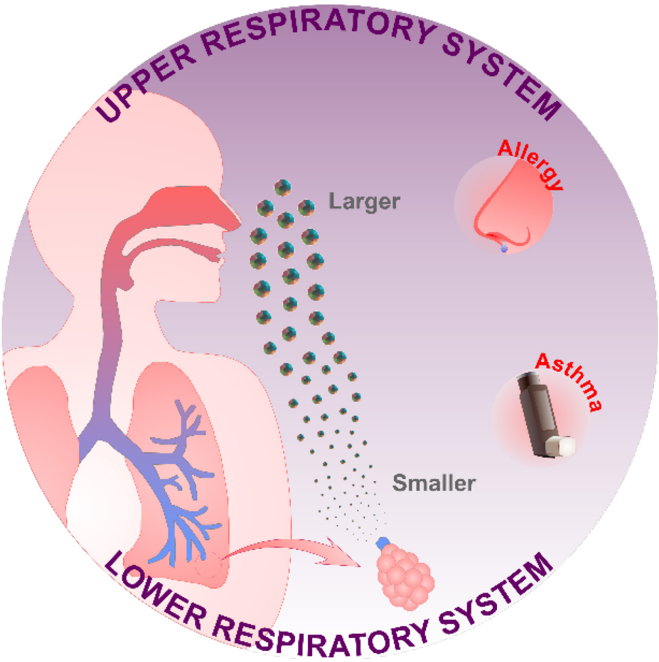
The number of waste composting sites, which can be large sources of outdoor bioaerosols, have increased since the 1999 European Landfill Directive required waste to be diverted from landfill (7 to 8). In addition to the increased number of such facilities, growing urbanisation and expansion of city limits means more people can end up living near such sites. Consequently, they may experience greater exposure to outdoor bioaerosols (8).

Indoor bioaerosol exposures can be generated through a lack of ventilation, influx of outdoor bioaerosols through windows, doors and ventilation systems, and increased insulation within buildings leading to the growth of fungi, which in turn release spores into the air (1, 3). Normal human activity within buildings, such as moving from room to room and cleaning, can affect the generation and movement of bioaerosols (3). The presence of pets or pests can lead to shedding of fur, dander, and other allergens as well as the generation of particles when cleaning out pet housing for smaller animals. House dust mite is also a common component of indoor bioaerosols. Indoor bioaerosols can account for up to 34% of indoor air pollution (1,3,9) and with ~80% of individuals in Westernised countries spending the majority of their time indoors, these indoor bioaerosols can represent a significant environmental exposure (9).

How are they associated with health?

Bioaerosols are inhaled as we breathe. Bioaerosols can become trapped in different parts of the respiratory system depending on their size. The smaller the particle, the further it can penetrate into the respiratory system, with those >10μm becoming trapped in nose and upper airways and those <10μm reaching the lower airways and lungs (Figure 3). Particles larger than 10μm, such as larger fungal spores and pollen, will deposit in the upper airway such as in the nose, throat, and trachea (2, 4). The upper portions of our airway have mechanisms that allow our immune systems to effectively deal with these biological particles, including mucus production and ciliated cells, which together trap and move particles and dead cells from lungs into the throat. Particles less than 10um, including smaller fungal spores, can easily penetrate into the lung and reach the bronchioles and alveoli (2, 5).

Figure 3. Inhalation of bioaerosols



Bioaerosols can both positively and negatively impact health. Exposure to microbes, particularly during early life, is beneficial for the normal development of our immune systems, and for most healthy individuals bioaerosols cause little adverse health effects. However, in sensitive individuals, exposure to bioaerosols has been associated with a range of acute and chronic adverse health effects and diseases (4). Symptoms are mostly respiratory in nature and can include coughing, wheezing, sneezing and shortness of breath, but other non-respiratory symptoms and health effects have been reported, such as gastrointestinal distress, fatigue, and headache (4). Allergic rhinitis (or hay fever) and asthma are among the most common respiratory conditions and have an increasing prevalence, especially in the Westernised world (9).

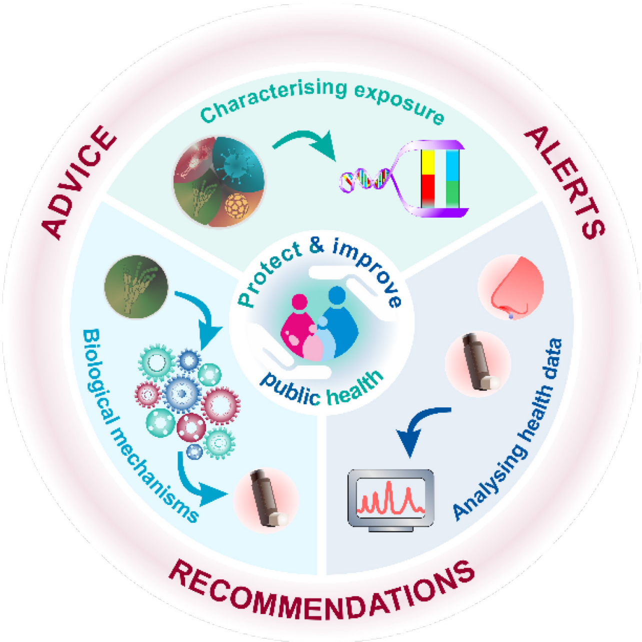
Those with pre-existing respiratory conditions (such as asthma, chronic obstructive pulmonary disease (COPD), bronchitis, or cystic fibrosis) or those who suffer from allergies to airborne particles (such as pet fur, fungi, or house dust mite) can be more prone to experiencing symptoms from exposure to bioaerosols. It is estimated that 10% to 20% of the general population are sensitised to animal fur from pets such as cats and dogs (9, 10), 6% to fungi (11) and 1% to 2% to house dust mite (12). Sensitisation to fungi or house dust mite rises to 20% to 70% in those with respiratory conditions such as asthma, cystic fibrosis, and COPD (9,12 to 15). In addition, approximately 10% to 15% of households experience dampness, a source of indoor fungi. Over time, continued exposure to fungi in damp houses may lead to sensitisation, inflammation, and allergy in residents (9).

Other at-risk groups include those who are immunocompromised through non-respiratory issues, such as those with cancer who are undergoing chemotherapy, and patients with immune diseases and disorders, such a HIV and chronic granulomatous disease. These groups are more at risk of infection from the microbes found in bioaerosols. Furthermore, those who are more likely to experience higher workplace exposures to bioaerosols, such as farm workers or workers at composting facilities, may have increased risk of adverse, mainly respiratory, health effects (3, 4, 16).

What work is UKHSA involved with?

The UK Health Security Agency (UKHSA) currently works on several projects that look at bioaerosols exposures and their effects on respiratory health. These projects can be split into 3 themes: characterising exposures to bioaerosols, collating and analysing associated health data, and understanding the biological mechanisms linking specific exposures with health outcomes (Figure 4). Through such work UKHSA can provide both the public and healthcare professionals with the best advice, alerts, and recommendations to help protect and improve health.

Figure 4. Key areas of UKHSA research into bioaerosols



One of the key funding initiatives behind UKHSA's research into bioaerosols is the 2 Environmental Exposures and Health (EEH) Health Protection Research Units (HPRUs) funded by the National Institute for Health Research (NIHR). As part of these EEH HPRUs, UKHSA collaborate with the University of Leicester and the Health and Safety Executive, and Imperial College London and the MRC Toxicology Unit.

Characterising exposure

We need to better understand what microbes people are exposed to in different environments. Since characterisation studies tend to centre around bacteria, our current focus is on fungi, which are known to induce and exacerbate allergy and asthma in susceptible individuals. We are using DNA sequencing technologies to analyse the fungal composition of different samples and environments, including soils from different urban greenspaces (17), daily outdoor air samples from urban and more rural locations, and dust collected from overground and underground railways stations.

Analysing health data

The next step is to integrate improved exposure information with health data to identify the associations between specific bioaerosols and health outcomes. Our systematic reviews and epidemiological studies on the public health risks of bioaerosol emissions from composting sites and intensive farms show that, while data is limited, there is qualitative evidence linking bioaerosol emissions to poorer respiratory health in nearby residents (4, 7, 8). We are currently integrating seasonal changes in outdoor fungal bioaerosols with seasonal asthma and allergy spikes, in collaboration with UKHSA's Real Time Syndromic Surveillance Team and the University of Leicester, to identify specific fungi associated with such symptoms.

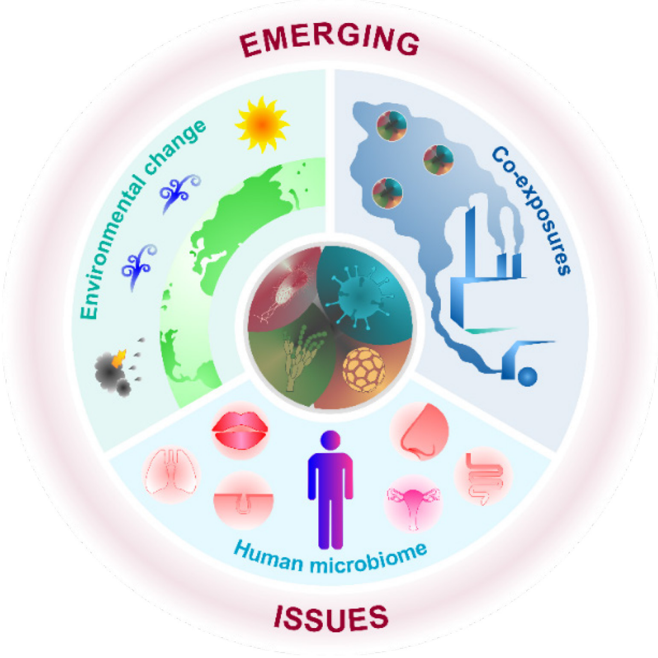
Biological mechanisms

It is then vital to investigate the biological mechanisms underlying associations between specific exposures and health outcomes. Work includes reviewing the current understanding of cellular responses to fungal exposure and how this differs in respiratory diseases such as asthma, using experimental models to address the knowledge gaps identified.

What are the emerging issues in bioaerosol research?

There are a number of key emerging issues within bioaerosol research including co-exposures with other air pollutant particles, the impact of environmental change on bioaerosol composition and concentrations, and how the human microbiome effects respiratory health and vice versa (Figure 5).

Figure 5. Emerging areas of interest to UKHSA



Co-exposures

It is well known that bioaerosols and non-biological air pollution (such as particulate matter and exhaust fumes) can individually impact human health and contribute to a number of chronic respiratory effects (9). However, there have been limited studies looking at the additive effects of simultaneous exposures, and how they may affect both healthy and non-healthy populations (such as those with asthma) (2). There is growing evidence that interactions between non-biological and biological particles can significantly alter their health effects. For example, ultra-fine diesel particulates can dampen the body's immune response to infectious agents (2), and black carbon can increase the pathogenicity of bacteria (18).

Environmental change

Climate change can alter biodiversity as well as speeding up plant growth rates. This in turn can lead to changes to bioaerosol composition and concentration. For example, in urban areas with high carbon dioxide ragweed has been shown to flower more quickly, resulting in increased pollen production (6, 9). In addition, flooding is becoming more widespread with environmental change, potentially increasing the prevalence of mould and dampness in housing (9). Changing climates can also affect environments differently such that alterations in bioaerosol composition and concentration will vary between different environments (such as inner city versus rural). Ultimately, such changes may alter exposures and the subsequent development or exacerbation of allergic airway disease within different populations depending upon their local environments (6).

Human microbiome

Our bodies are hosts to a large number of microbes. The collection of microbes that live on and within us (termed the human microbiome) are known impact our health. Several microbiomes exist within humans, including the well-recognised gut microbiome and the more recently discovered respiratory microbiome (composed of the nasal, oral, airway and lung microbiome). Evidence is increasing of a gut-lung axis, where our gut microbiome can influence our respiratory health and microbiome and vice versa (19) both in a beneficial (immune development) and detrimental (allergy) manner.

Conclusion

Bioaerosols are airborne particles composed of biological material such as fungi, bacteria, viruses, and pollen. While they are naturally present within the air we breathe, some human processes can alter their biological composition or numbers. Bioaerosols can help promote normal immune development but can also be responsible for a range of acute and chronic health effects. Therefore, it is essential that we understand what we are being exposed to, how we are being exposed, who is being exposed, what the health consequences are, and what biological mechanisms are involved. UKHSA is involved in research addressing these questions, linking in with the wider UK Research and Innovation (UKRI) funded clean air programme, so we can better understand the public health benefits and risks of bioaerosols and how they can be promoted or mitigated through improved advice, alerts, and recommendations to both the public and healthcare professionals.

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UKHSA involvement in UKRI Clean Air Programme research networks

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Introduction

The UK Research and Innovation (UKRI) Clean Air Programme aims to bring together leading researchers from across atmospheric, medical, and social science to better predict exposure to air pollution and its effects on vulnerable groups, such as children and the elderly. It also aims to identify practical and usable solutions to help policymakers and business protect health and work towards a cleaner economy. The UKRI Strategic Priorities Fund (SPF) has made research and innovation investment of £42.5m, delivered across 2 waves of funding. The first wave of investment (£20.5m) supported multi-disciplinary research and innovation to stimulate solutions for clean air through predictive understanding of future air quality challenges, a systems approach to analysis, new technologies and innovative policy and practice interventions to benefit vulnerable groups, improve public health and support clean growth.

Through a second wave of investment (£22m) focussed on the indoor/outdoor interface, the programme aims to equip the UK to proactively tackle new and emerging air quality issues. These relate to changing emissions (such as from energy, transport, or soil and ground gas affected by climate change) and exposure patterns, the need to evaluate exposure across all outdoor and indoor environments as a continuum, and the impacts of exposure to air pollutants on vulnerable groups of people. Six interdisciplinary networks were funded for the period 2020 to 2023, and UK Health Security Agency (UKHSA) staff are co-investigators, advisors, or participants in each of them. This article briefly describes the work of each network and any highlights of UKHSA involvement to date.

BioAirNet: Indoor/Outdoor Bioaerosols Interface and Relationships Network

BioAirNet, Principal Investigator: Frederic Coulon, UKHSA lead: Philippa Douglas

BioAirNet is led by Professor Frederic Coulon at Cranfield University. Its aim is to act as the leading voice for the UK BioPM (biological particulate matter) science community by taking a transdisciplinary approach to understand the complexity and connectivity among people, BioPM exposure and resultant health impacts and the indoor-outdoor continuum. BioAirNet comprises 4 themes, which together aspire to coordinate, widen, and inform community interactions; promote discovery science; attract and stimulate the next generation of academic leaders; develop effective engagement pathways; and translate the knowledge of the network beyond the UK.

Theme 1 is centred on BioPM sources, dynamics, and identifying research needs. It aims to prioritise the research for BioPM, develop a road map and white paper for implementation, and to identify and interact with all stakeholders in promoting solutions and influencing policy. Theme 2 is focussed on BioPM sampling and characterisation and aims to facilitate the translation of advances in fundamental science into technological solutions and process enhancements for end-users, stakeholders, and regulators. Theme 3, on human health, behaviour, and wellbeing, aims to translate the knowledge about BioPM sources and composition (Themes 1 and 2) to better understand the longer-term human exposure to BioPM and environmental impacts using computational modelling to estimate impact over large spatial scales. Theme 4 is focussed on policy and public engagement, which aims to understand the factors that might help influence mind-sets, engaging with potentially vulnerable groups from several different indoor-outdoor environments to explore risk perception and resulting behaviours.

BioAirNet is employing a range of activities and dissemination mechanisms to achieve its aims and aspirations. These include outreach, annual stakeholders network events; theme group meetings producing guidance, roadmaps, and policy documents; joint events with other networks; sandpit workshops; training, exchanges, short-term industrial placements, and annual events for early career researchers; and cross-disciplinary skills training. UKHSA staff have helped organise or participated in the launch and 4 theme events, and contributed to the Theme 3 outputs to date. They are Co-Leads on Theme 3 and input into the planned outputs across all themes.

Breathing City: Future Urban Ventilation Network

Breathing City, Principal Investigator: Cath Noakes, UKHSA lead: Jim Stewart-Evans

The Breathing City Network is led by Professor Cath Noakes at the University of Leeds. Its objective is to define a new integrated health-evidenced approach to urban and building ventilation design for vulnerable communities: The Breathing City. Quantifying and managing health risks from air pollution relies on understanding how the airflows that transport pollutants through outdoor and indoor environments result in human exposure. One of UKHSA's early contributions to the network was to begin to visualise and explore the connections between the different factors affecting airflows and their connection to people's exposures and health, using an interactive mind map.

The first theme of work within the network evaluates the approaches to couple indoor and outdoor flows, improve modelling of airflows, and explores the health effects arising from people's exposures to air pollution, noise and thermal comfort. The second theme focuses on health-centred ventilation design and incorporates a systematic literature review focussing on respiratory health. It also considers human behaviour and the way people interact with ventilation, as well as ventilation system design, and behavioural science experts in UKHSA helped inform the network's plans for surveys of ventilation behaviour. The network's third theme considers policy and regulation and aims to identify different stakeholders' needs for information and tools and how these might be addressed in future. This provides opportunities to address householders and vulnerable groups within the population and include wider healthcare and third sector perspectives when considering ventilation provision and practices.

Each theme, together with the wider network, features a series of workshops. Opportunities to get involved in events and activities, and funding for small-scale research projects, are highlighted on the project website. The network also runs a series of lunchtime seminars, and past presentations from UKHSA staff discuss different environmental hazards to health and interventions to reduce people's exposure. To watch past events and seminars, visit the network YouTube channel.

CleanAir4V

CleanAir4V, Principal Investigator: Christian Pfrang, UKHSA lead: Karen Exley

CleanAir4V is led by Dr Christian Pfrang at the University of Birmingham. CleanAir4V brings together researchers, stakeholders and industry practitioner and uses a multidisciplinary approach to identify, develop, and evaluate indoor air pollution solutions for 2 vulnerable groups (VGs): VGI are children (aged 0 to 16) and VGII comprises people with pre-existing conditions such as chronic obstructive pulmonary disease. These groups are the focus as they are most strongly affected by poor indoor air quality but have limited control over indoor environments such as schools, hospitals, and public transport.

To achieve its aims the network intends to:

- build a self-sustaining and interdisciplinary network of academics, industry, and other key stakeholders capable to deliver co-designed research and innovation for developing robust solutions that reduce the impact of air pollution on vulnerable groups
- cross-link to UK and international expertise to establish research gaps, effective behaviour and technology intervention opportunities and catalyse future cross-disciplinary research capability in the field of air pollution

HEICCAM

HEICCAM, Principal Investigator: Ruth Doherty, UKHSA lead: Sani Dimitroulopoulou

HEICCAM is an innovation research network integrating interdisciplinary researchers and stakeholders to develop indoor and outdoor air quality solutions as we transition to a low carbon future. The transition to a low carbon economy and policies to improve air quality have important implications for exposure to air pollutants in the connected indoor and outdoor environments. While the transition will generally lead to lower exposures to ambient air pollution, the effect on personal exposure indoors is unclear.

Measures to improve home energy efficiency typically entail reducing ventilation and hence air exchange. While beneficial in decreasing the penetration of pollutants from the outdoor environment, they may increase gaseous and particle pollutants from indoor sources.

The limited understanding of these impacts reflects an evidence gap that is especially important for vulnerable groups including children, the elderly and those with pre-existing illness. The HEICCAM network seeks to address this gap.

To achieve this the network intends to:

- convene an interdisciplinary, multi-sectoral network to improve understanding of key trade-offs and future challenges relating to the consequences of climate change and clean air policy measures on exposure to air pollutants in the connected indoor and outdoor environments
- facilitate interactions between early career and established researchers across air pollution, building design, public health, and behavioural science disciplines to help grow capability in transdisciplinary research in this domain
- undertake targeted evidence synthesis, modelling studies and empirical research to guide network discussions
- co-produce agenda setting papers for science and policy audiences outlining critical policy and research needs aligned to the clean air programme
- disseminate the findings of the network to the wider research community, stakeholders and the public and promote impact on policy, practice, and future research

TAPAS

TAPAS, Principal Investigator: Paul Linden, UKHSA lead: Sani Dimitroulopoulou

The TAPAS (Tacking Air Pollution at School) network connects stakeholders across academia, education, public policy, civil society, and business, working together to support the development of healthy schools by improving air quality. The objective is to bring together interdisciplinary expertise to develop the research base to design and operate healthy schools in the environment of the future.

To achieve this the network intends to convene groups with the aims of:

- understanding indoor environmental quality problems in schools
- understanding the potential solutions
- prioritising the solutions and taking an integrated approach
- disseminating information and involving schools and children

TAPAS organise regular seminars, usually on a weekly basis (Thursdays, 1pm to 2pm), inviting national and international scientists to present their school-related work. The seminars started in February 2021 and Sani Dimitroulopoulou was one of the first speakers to present UKHSA work on air quality around schools (1, 2). Previous seminars can be watched from the TAPAS website, where information can also be found regarding upcoming events.

In May 2022, members of the TAPAS and the Future Urban Ventilation Networks attended a workshop in Paris hosted by the networks in collaboration with the Observatoire de la qualite de l'air interieur (OQAI). This brought together researchers and policy makers from France and the UK to discuss indoor air quality in schools and other indoor environments, learn from the French expertise on indoor air, and stimulate some fabulous discussions. UKHSA was represented and new collaborations across La Manche may help us to shape the future of indoor air quality in the UK.

TRANSITION

TRANSITION, Principal Investigator: Suzanne Bartington, UKHSA lead: Charlotte Landeg-Cox

TRANSITION is a UK-wide Clean Air Network programme which is led by Dr Suzanne Bartington at the University of Birmingham in collaboration with 9 UK universities and cross sector partners. It seeks to deliver air quality and health benefits associated with the UK transition to a low emission transport economy. The network has 4 themes: 1) characterising emerging air quality challenges and risks, 2) understanding transport choices and behaviours, 3) supporting industry led research and innovation, and 4) co-creating a framework for policy solutions. These themes are being explored using a range of activities including summits, workshops, discovery and innovation studies, placements, and public outreach activities.

An Environmental Public Health Scientist from UKHSA participated in the online network launch workshop in November 2020. The objective was to identify new emerging indoor and outdoor air challenges and risks associated with transport decarbonisation over the next 10 years. The workshop was attended by a variety of stakeholders representing 45 organisations, and breakout groups encouraged structured and detailed discussions about road transport, public transport, active travel, and built and indoor environments. A report ‘Characterising emerging air quality challenges and risks associated with transport decarbonisation’ summarised the discussions and provides recommendations for priority research areas.

On Clean Air Day in June 2021, a webinar ‘What do we know about in-vehicle air quality?’ was held to explore and discuss differences in air pollution exposure inside buses, trains, motor vehicles and along active travel routes in the UK. Dr Christina Mitsakou, an Environmental Public Health Scientist in UKHSA, presented the findings of a recent evidence review on ‘Assessing the exposure to air pollution during transport in urban areas’. The webinar recording is available online.

The network funded 4 research projects in the first round of its Discovery and Innovation fund, with a UKHSA Environmental Public Health Scientist acting as an advisor to one of them. These projects aim to improve air quality by reducing transport emissions and full reports, data and factsheets are available on the network website.

TRANSITION Clean Air Network is scoping knowledge mobilisation on air quality and health from transport and developing briefing notes and hosting webinars to support stakeholders, including local authorities across the UK. Further details of this work are provided on the network website and monthly newsletters. Subscribe to the newsletter via the home page of the website or by emailing info@transition-air.org.uk

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Theme 2: Influencing and supporting stakeholders

UKHSA aims to use the data, analysis, and scientific research that it produces to inform and influence the priorities of national and local government. There are complex relationships between air pollution and other environmental stressors (such as climate change and noise) and between air quality, health, and other policy objectives. This requires a holistic approach when supporting policymakers and influencing others to take action to reduce the health burden associated with air pollution and address vulnerable groups and health inequalities. Through the Cleaner Air Programme, UKHSA advises and influences decision-makers with evidence and support in various contexts including:

- hosting 2 annual UKHSA air quality events to share ongoing work in the air quality field – the Annual UK Review Meeting on Outdoor and Indoor Air Pollution Research event brings together researchers to share the latest evidence and an Air Quality and Public Health Stakeholder Seminar looks at actions to improve air quality, sharing a range of presentations from key internal and external stakeholders
- supporting Global Action Plan with the Clean Air Hub resource, by ensuring the latest and most robust evidence is used when messages are developed
- working with COMEAP to support government in setting fine particulate air pollution ($PM_{2.5}$) targets under the Environment Act
- support air quality action in Wales
- tools and resources to support local government, examples include work with the Greater London Authority (GLA) to develop Borough Air Quality Guidance reports for Public Health Professionals (1) (described in an article in this special issue showcasing UKHSA's wider work in London) as well as activities with Yorkshire and Humber
- as a 'Category 1' responder UKHSA support the local and national management of incidents and emergencies that threaten health (including chemical, biological, radiological and nuclear events) – further details of the UKHSA's response to incidents that affect air quality, such as fires, wildfires, and air pollution episodes, can be found in the concluding article in this section

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Setting air pollution targets under the Environment Act 2021

Advice from the Committee on the Medical Effects of Air Pollutants (COMEAP)

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Abstract

The Environment Act (2021) requires government to set 2 legally binding air quality targets, one of which must be as an annual average concentration of fine particulate air pollution ($PM_{2.5}$). Advice from the Committee on the Medical Effects of Air Pollutants (COMEAP) confirms that, to benefit public health, targets should aim to reduce the long-term average concentration of $PM_{2.5}$ to which the population is exposed: evidence from recent studies has shown effects in cohorts exposed to low air pollution concentrations and has not suggested a 'safe' concentration of $PM_{2.5}$ below which no effects are observed.

Introduction

The Environment Act (2021) requires government to set at least one long-term environmental target in each of 4 priority areas: air quality, biodiversity, water, and resource efficiency and waste reduction (1). Targets established must be objectively measurable and time-bound, and the government must consider them achievable. The Act also specifies that the Secretary of State must seek independent expert advice when establishing the targets, and that the targets must be set in Statutory Instruments by 31 October 2022.

For air quality, the Act establishes a duty to set both a target based on annual mean fine particulate air pollution ($PM_{2.5}$) concentrations, and an additional long-term target. A policy paper on environmental targets, published in August 2020, outlined the Department of Environment, Food and Rural Affairs' (Defra's) intention that both targets will relate to long-term exposure to $PM_{2.5}$, with a population exposure reduction target (PERT) being established in addition to a concentration-based target (2).

Defra requested independent expert advice on these proposals by consulting with the government's independent expert advisory committees on air quality: Defra's Air Quality

Expert Group (AQEG) and the Department of Health and Social Care's (DHSC) Committee on the Medical Effects of Air Pollutants (COMEAP). Defra has also drawn on other advice and work commissioned from external experts (3), such as work by Imperial College London and King's College, London examining the achievability of the World Health Organization's (WHO) long-term Air Quality Guideline for $PM_{2.5}$ which, at that time, was 10μg/m^3 as an annual average.

Advice provided to Defra by AQEG and COMEAP was published in July 2021 (4). In March 2022, COMEAP published a short update to its advice in the light of updated Air Quality Guidelines published by WHO in September 2021. In this paper we summarise some of the key points included in COMEAP's response.

Methods

COMEAP was asked to consider a range of questions related to the health evidence relevant to developing targets for $PM_{2.5}$. Advice on quantification of effects, for use in assessing the health impact of proposed interventions to reduce air pollution concentrations, was also requested. COMEAP discussed the evidence and developed responses during a number of meetings and via correspondence. The specific questions asked, and COMEAP's full responses, are available in COMEAP's published advice note (4).

Results

Long-term or short-term average concentrations

While COMEAP recognised that the intention was to develop targets for $PM_{2.5}$, it reminded Defra that the health benefits of reducing concentrations of other pollutants (for example, nitrogen dioxide (NO_2) and ozone (O_3)) should not be overlooked. For $PM_{2.5}$, COMEAP agreed that a focus on reducing long-term average concentrations is appropriate. The committee advised that it is clear from epidemiological studies that both long-term and short-term average concentrations of $PM_{2.5}$ are associated with health effects, and that associations with long-term average concentrations represent a bigger effect on public health. Although panel and volunteer studies have demonstrated that short-term exposure affects health, the committee advised that this does not necessarily indicate a need for a separate short-term target or standard. This is because frequency distributions of daily average concentrations of $PM_{2.5}$ are fairly stable year-on-year, suggesting that policies to reduce long-term average concentrations would also be effective in reducing peaks of short-term average concentrations.

The committee also noted that both long-term and short-term exposures affect health, but likely in different ways, and that the relative importance of long- and short-term exposures likely varies depending upon the health endpoint under consideration. People with pre-existing disease are likely to be most sensitive to effects of short-term exposure, including effects that might not have occurred without peaks of elevated concentrations. Long-term exposure likely has the potential to affect everyone, by contributing to the initiation and progression of disease. The committee, therefore, suggested that an assessment should be made of the impact on short-term (for example, daily) average concentrations that would result from the interventions needed to achieve the long-term targets.

Developing a concentration 'Limit Value' type target for long-term exposure to $PM_{2.5}$

Questions related to developing a concentration-based 'Limit Value' type target, which should not be exceeded, were concerned with whether it could be informed by the shape of the exposure-response curve (for example whether there was evidence of a threshold below which there was no adverse effect) and the lowest concentrations for which there was evidence of an effect.

Previous evaluations of the health evidence had suggested little evidence for a threshold of effect, at the population level, below which there is no health harm. Recent evidence indicates associations with adverse effects at lower concentrations than had previously been studied. For example, a large study in Canada reported adverse associations in a population in which the mean $PM_{2.5}$ concentration was 6.3µg/m^3 and the 5th percentile was 3.0µg/m^3 (5). The new studies have not indicated a threshold of effect below which there is no harm, nor a threshold below which there are decreases in relative risk associated with long-term average concentrations of $PM_{2.5}$. COMEAP noted that there is a suggestion from some recent studies that the relative risk might be greater at lower concentrations. However, there is, as yet, no consensus on the shape of the concentration-response function at lower levels of $PM_{2.5}$. COMEAP advised that the recent evidence suggests that continuing to reduce $PM_{2.5}$ concentrations as much as possible would benefit public health.

Regional targets for exposure reduction

Defra asked what health evidence (such as risks to populations in different regions) they should be aware of when considering whether regional targets could be developed. COMEAP explained that air pollution would be expected to have a bigger adverse effect on populations with poorer underlying health. However, the regions potentially under consideration by Defra for separate targets were likely too large for the granularity in socioeconomic and health status to be well reflected.

Metrics for particulate matter

COMEAP agreed with the suggested metric of $PM_{2.5}$ (mass concentration of fine particulate air pollution) given the uncertainties in distinguishing which components, sources or size fractions might most adversely affect health. COMEAP acknowledged that it is almost certainly the case that some components or sources of particles are more detrimental to health than others. Nonetheless, at this stage, the health evidence continues to suggest that a focus on $PM_{2.5}$ mass remains appropriate. Two recent reviews (6, 7) confirmed and strengthened COMEAP's previous views on this topic (8).

Groups at risk from the health effects of air pollution

COMEAP was asked whether the health evidence suggested that targets should be focused on delivering improvements to the whole population or on reducing exposures of highly exposed or susceptible groups, and who these groups comprise. COMEAP's view was that reducing exposure of the whole population would achieve the greatest overall public health benefit. It would also reduce the exposure of those most at risk.

Older people, and people with heart and lung conditions, are known to be susceptible to the effects of short-term exposures. COMEAP suggested that some risk factors may be less obvious; for example, some genetic backgrounds, lifestyle choices or co-exposure to other pollutants. Other vulnerable life stages likely include pregnancy and early childhood when the body is developing. Groups exposed to increased air pollution include those who spend considerable amounts of their working life in vehicles or at roadsides, and those living close to busy roads. There is evidence to suggest that there are inequalities in exposure to pollution, with ethnic minorities and lower socioeconomic groups more highly exposed to particles and NO_2. It might be difficult to incorporate consideration of inequalities within the formal targets framework, but COMEAP suggested that Defra could consider the use of nested modelling and sensitivity or supplemental analyses to assess whether interventions (proposed or implemented) reduce inequalities in exposure or have undesirable consequences for inequalities.

Assessment of the target

How compliance with the targets will be assessed, including defining where they will apply, is an integral part of their development. Information on exposure, and regarding exposure assessments used in the epidemiological evidence base, was requested to inform Defra's consideration of which types of locations should be included. COMEAP noted that sites near emission sources (for example, traffic-orientated monitoring sites) will likely experience higher concentrations than background locations. It suggested that while roadside exposure might be unlikely to make a significant contribution to $PM_{2.5}$ exposure at a population level, a study had found that a large proportion (approximately 30%) of the population in London lives within 50m of a major road. In addition, although roadsides represent small areas within any specific local authority area, they equate to a large area across the country as a whole.

Quantifying health effects associated with $PM_{2.5}$ concentrations and interventions to reduce $PM_{2.5}$ concentrations

COMEAP was also asked whether recent systematic reviews provided a suitable basis for updating its recommendations for quantifying the benefits of reducing air pollution. In response, COMEAP has reviewed some of its recommendations for quantification and has published updated advice (9, 10).

Discussion

Since COMEAP published its advice to Defra, the World Health Organization (WHO) has published updated Air Quality Guidelines for a number of air pollutants, including $PM_{2.5}$ (11). WHO's report confirms COMEAP's views that recent studies provide evidence for effects at lower concentrations than previously, and that $PM_{2.5}$ remains the most appropriate metric for targets related to airborne particulate pollution.

In summary

COMEAP's advice regarding the available health evidence has informed Defra's proposals for targets for air quality under the Environment Act 2021. Important points from the advice were that, in order to maximise benefits to public health, the targets should include a focus on:

- reducing long-term average concentrations of $PM_{2.5}$
- reducing exposure of the whole population
- continuing to reduce exposures even where concentrations comply with a 'limit value' type target
- using $PM_{2.5}$ (mass concentration) as the metric

In addition, Defra was advised to:

- assess impacts on short-term (for example, daily) average concentrations
- consider the health benefits of reducing concentrations of other pollutants (for example, NO_2 and O_3)
- assess whether interventions (proposed or implemented) reduce inequalities in exposure or have undesirable consequences for inequalities

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Air Quality in Wales: an update on policy and practice

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Introduction

The importance of the people of Wales breathing clean air continues to be a priority for policy makers, particularly the need to embed the positive changes in travel behaviours that resulted from COVID-19 to support longer term ambitions to reduce air pollution. This paper provides a brief update on legislative and public health efforts to improve air quality in 2021.

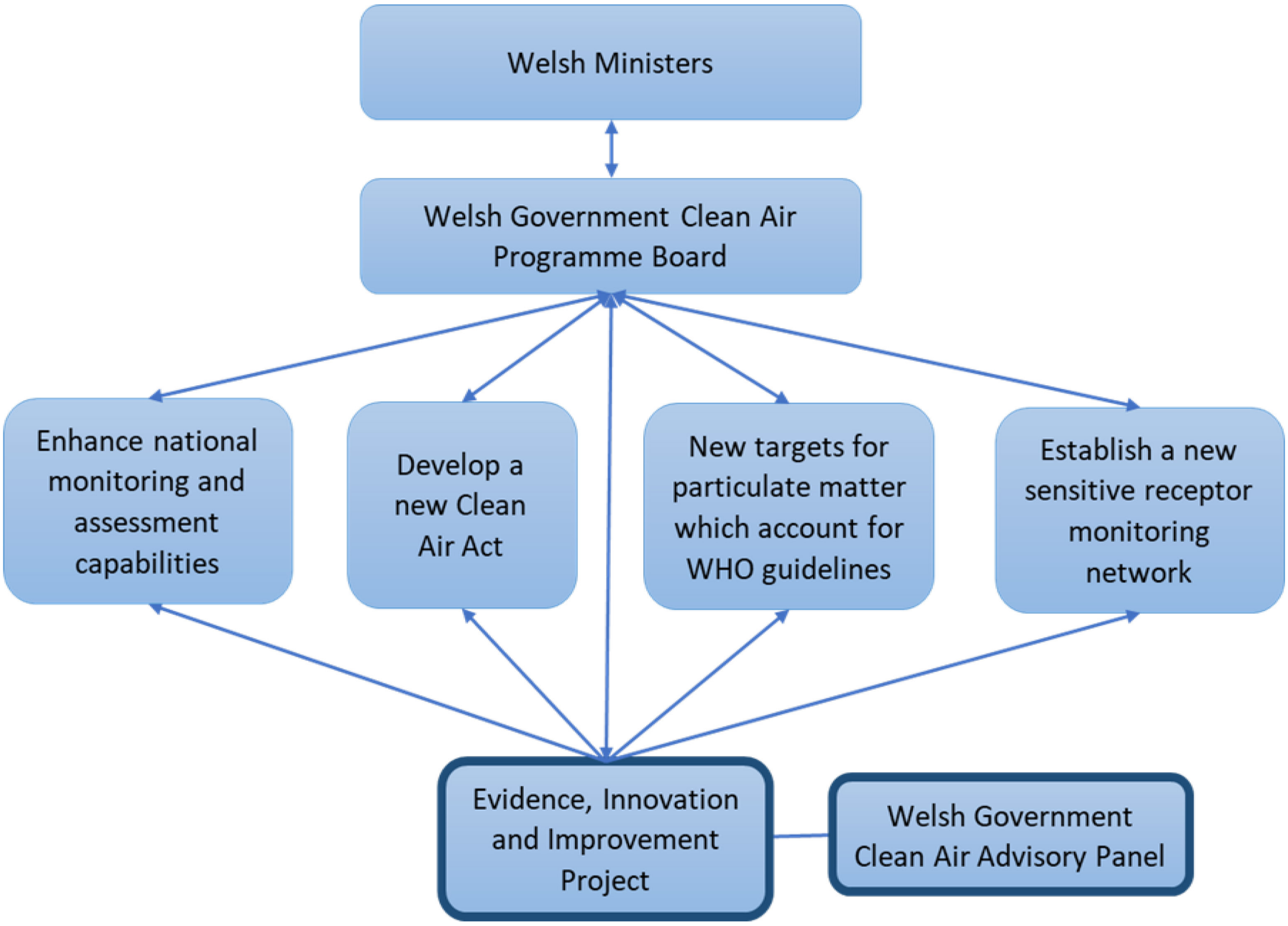
Clean air policy

On 13 January 2021, the then Minister for Environment, Energy and Rural Affairs, Lesley Griffiths, published a White Paper to support the development of a Clean Air Act for Wales (1). The ambition in Wales is to embed effective air quality standards into Welsh law so people in Wales can breathe clean air, so children can play in their communities and to reduce associated inequalities). The proposals in the White Paper, together with measures already set out in the Wales Clean Air Plan (2), include:

- powers to set air quality targets, including for $PM_{2.5}$, which consider the latest scientific evidence and international policy and guidance, such as WHO guidelines
- a requirement to review the Clean Air Plan at least every 5 years
- improving local air quality management by giving additional powers to local authorities to form multi-agency partnerships to address air quality, to tackle idling vehicles (especially outside schools and healthcare settings) and to better manage and enforce the burning of unauthorised domestic fuels
- a duty on public and private organisations to help the public better understand the risks of air pollution and to encourage positive behaviour change

To support these measures, Welsh Government established a Clean Air Advisory Panel (CAAP) of experts to independently advise on and provide scientific evidence to support the development of clean air policy. The Panel includes representatives from academia, Public Health Wales, Natural Resources Wales, NGOs such as Healthy Air Cymru, as well as a range of Welsh Government Departments including officials from Transport and Air Quality policy. Working with the Welsh Government Clean Air Programme Board, current work areas include reviewing evidence to support the development of new air quality targets, work to improve the air monitoring network and advice on action around domestic combustion (Figure 1).

Figure 1. The Welsh Government Clean Air Advisory Panel



Powers to set new air quality targets

Welsh Government asked CAAP to review the case for new air quality targets, including for $PM_{2.5}$ which has the most significant impact on health. The recent update of the WHO air quality guidelines is part of the evidence base considered (3). The current policy in Wales is to introduce a Clean Air Act that is consistent with WHO guidance, although this does not necessarily mean direct implementation of the new WHO guidelines on $PM_{2.5}$ and other pollutants.

Historically air quality targets have been presented as a standard or limit value for the entire country. However, for some pollutants these standards are higher than recognised no-effect thresholds and monitoring locations may not reflect public exposure as compliance is typically measured at a single location such as a roadside. Furthermore, such targets do not necessarily encourage action if the target is being met. As a result, CAAP considered the merits of a twin-track approach with the traditional limit value running alongside an exposure reduction approach where the concentration is averaged across either the whole country or specific areas. One particular approach considered is that of the population-weighted mean concentration (PWMC) where exposure is calculated by weighting mean annual concentrations of, for example, $PM_{2.5}$ by the population of a defined area. The CAAP also considered whether this metric can be refined by using health or deprivation data. The basis for this discussion is that in Wales there is a strong relationship between air pollution concentrations and deprivation.

Air pollution, COVID-19 and inequalities

Included in the many questions surrounding coronavirus (COVID-19) is the effect of air pollution and air pollution exposure on the spread of disease and risk, and severity, of infection (this is explored in more detail in a dedicated article in this issue). Air pollution can affect lung development and function and increase susceptibility to respiratory infections. Therefore, it is certainly plausible that air pollution could play a role in the incidence and severity of COVID-19. There are also some suggestions that incidence is higher where air pollution is greater, but these areas tend to be the most densely populated, are more deprived and have large multi-ethnic populations. Whatever the role, if any, air pollution is found to have in the spread of COVID-19, the pandemic highlighted health and societal inequalities and inequities, including those relating to air quality. To address these, Public Health Wales is working with local authorities and academics as part of the CAAP that will make recommendations to Welsh Government on policies that will protect the most vulnerable from air pollution.

The pandemic has also shown how transport and travel affect air pollution. Work commissioned by Welsh Government and undertaken by the consultants, Ricardo, illustrated the changes in different air pollutants during lock-down (4). It showed that travel and transport are significant contributors to some air pollutants, specifically nitrogen oxides, and that changes in the need to travel and mode of travel can have significant benefits for air quality. Policies that recognise these changes and aim to support their adoption in the long term are likely to benefit air quality and, therefore, health. However, data from the lock-down also demonstrated that for particulate matter the situation is far more complex, and concentrations are less dependent on travel-related emissions. This analysis has shown that more comprehensive data is needed on $PM_{2.5}$ in Wales to inform any decision around future health-based targets and other policy initiatives.

The CAAP has also considered the impacts of changes in air quality during the COVID-19 pandemic between March and October 2020 and the implementation of intervention measures (5). They concluded that current evidence for long-term exposure to air pollution and COVID-19 mortality was inconclusive and there were questions over the robustness of data, variable collinearity and confounders and the analytical methods applied.

The pandemic also had other impacts on air quality in Wales. Changes in air pollution concentrations do not necessarily translate to similar changes in exposure. While the lockdown decreased exposure to some traffic-related pollution, it may have increased exposure to air pollution in the home. In Wales, we strengthened our public health surveillance on carbon monoxide to reflect the fact that people are spending more time at home.

Data from the 3 Fire and Rescue Services in Wales showed that there were small increases in call outs to domestic waste fires, probably due to recycling facilities being closed and people being at home. They also reported an increase in callouts and anti-social activities that appeared to be linked to the lack of organised firework displays around Bonfire night in 2020. Data from air monitoring stations across Wales showed a marked deterioration in air quality on the evening of the 5 November and higher air pollution levels than in previous years, although the calm still weather conditions were a contributing factor. Efforts are on-going to establish whether there were any associated health effects of this change, both in terms of burn injuries and respiratory outcomes.

Air quality and public health surveillance

Understanding variations in outdoor air pollution and exposure is important to inform public health risks, especially at local level. The need for a robust air quality surveillance system underpins Welsh Government work on developing clean air policies in Wales. Recognising this, and to start to address the challenge, Public Health Wales has developed an interactive tool: 'Outdoor Air Quality and Public Health in Wales' (similar to a tool in England described in a separate article in this issue) (6). This evolving online tool is easy to access and free to use, and it can be accessed online. Figure 2 is a screenshot showing mapped pollutant concentrations at local authority level; Figure 3 shows how data can be selected based on pollutants, authority areas, concentration bandings, and population susceptibilities based on age or deprivation.

Figure 2. Mapping of annual nitrogen dioxide air pollution in Wales using the online tool

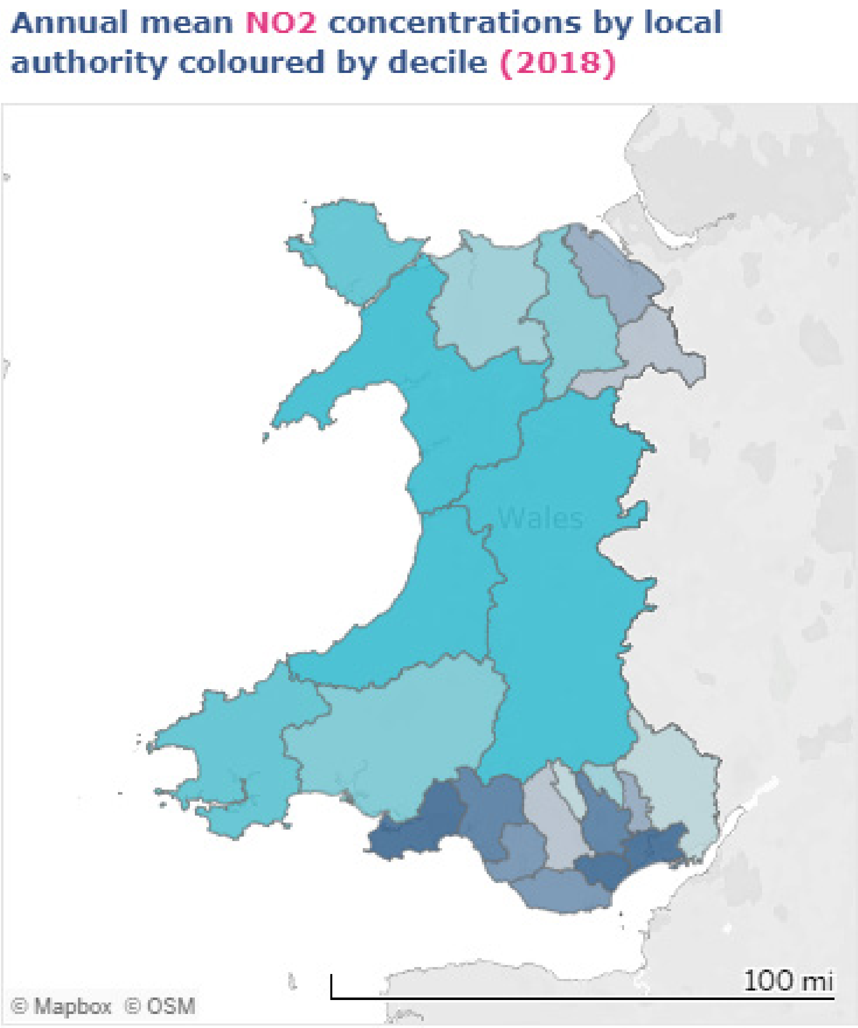
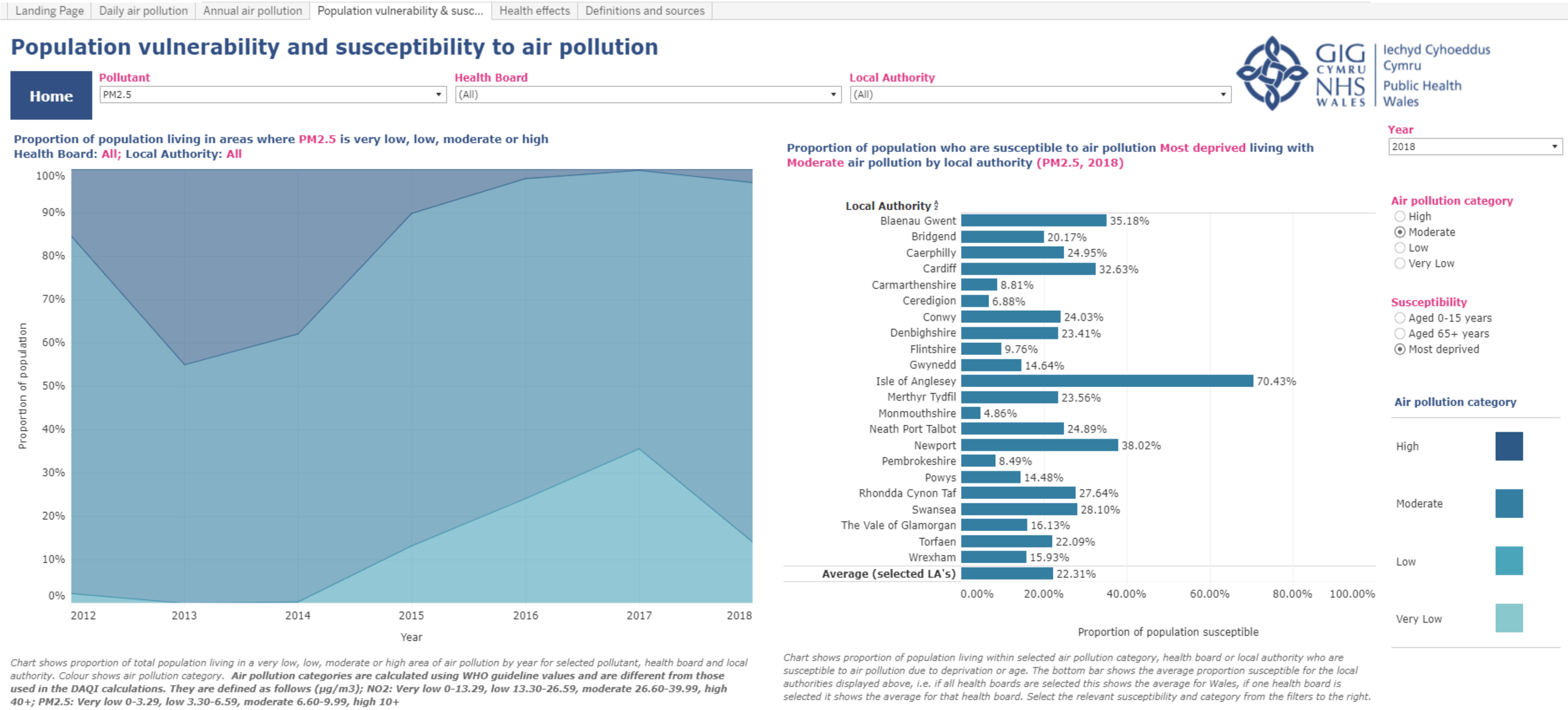


Figure 3. Mapping of population vulnerability and susceptibility using the online tool



The tool comprises different components that complement the common risk assessment used by local authorities. Risk assessments should be underpinned by the idea that air pollution is not an isolated environmental problem: it interacts with other health and social determinants, meaning there is merit in assessing the risk and impacts in the broadest possible public health context. In doing so, air quality assessments can connect with multi-disciplinary work on active travel, overweight and obesity, deprivation, and inequalities. The 4 components of the tool are:

- short-term air pollution (daily variation) – the monthly proportion of days where air pollution was low, moderate, high, or very high using the Daily Air Quality Index (DAQI)
- annual air pollution (long-term variation) – population-weighted annual mean pollutant concentrations (for nitrogen dioxide and particulate matter)
- population vulnerability and susceptibility to air pollution – exposure risk by different sub-populations by age and socio-economic status
- health effects of long-term air pollution exposure – mortality burden estimates attributable to air pollution (fine particulate matter and nitrogen dioxide combined)

Of particular importance to public health is the population vulnerability, susceptibility, and impact component. This component assesses risks amongst those who may live in areas where air pollution concentrations are higher (vulnerability), and amongst those who are more at risk because of age or socio-economic deprivation (susceptibility). The 'health effects' component provides data which estimate mortality from combined exposures to fine particulate and nitrogen dioxide pollutants (using recent methods recommended by the Committee on the Medical Effects of Air Pollution). These data are also supported by advice and guidance from Public Health Wales including an air pollution and health statement (7).

Cutting the default speed limit in Wales

There is growing international evidence and recognition that higher traffic speeds in residential areas present significant public health harms. Even before COVID-19, the Welsh Government recognised the need to address harms associated with the road traffic environment. These range from direct effects, such as road traffic injuries and fatalities, to broader, indirect effects, including air and noise pollution, isolation, loneliness, and community severance. Included in these efforts were a pledge to cut the default speed limit from 30mph to 20mph where people live, work and play (8).

While there are lengths of road across the UK that are already restricted to 20mph, particularly around schools, the full potential benefits of the change are not being realised by the variation in practice. As well as reducing the harms listed above, a default 20mph speed limit has also been found to increase small business viability, increase social inclusion, and narrow the stark health inequalities associated with the road traffic environment. Perhaps paradoxically, speed restrictions are also suggested to reduce congestion, because vehicles are more able to merge at junctions.

Linked to reduced congestion, although a mixed picture, there is some evidence that the introduction of 20mph encourages ‘smoother’ driving, with less acceleration and braking, potentially leading to some positive effects on air quality (8). These effects are difficult to quantify because of the challenges of monitoring air quality across the road network, where only relatively short sections are currently 20mph, and because of other confounding factors. There is also evidence that 20mph restrictions encourage more people to walk and cycle instead of using the car. This will have the potential benefit of further improving air quality.

A default 20mph speed limit is to be introduced in Wales in September 2023. Scotland have recently announced a similar move planned by 2025; Spain, Norway and the Netherlands are also implementing such a change. The scale of these planned changes mean that more robust air quality outcomes data will become available over the next couple of years.

Ahead of the roll-out of the reduced speed limit in Wales, 8 pilot areas will trial the change to 20mph and will help collect data on a range of issues such as compliance, casualties, active travel, and economic and environmental impacts (9). Indicative air quality data collected at these locations will further support our understanding of changes in ambient air pollutant concentrations arising from this intervention.

In addition, Wales has introduced 50mph zones (from 70mph) in 5 locations in south and north-east Wales, specifically to reduce nitrogen dioxide air pollution. These zones have been in place since 2018, but from 4 October 2021 became enforced by speed cameras. Welsh Government estimate that since 2018, levels of nitrogen dioxide in the 50mph zones has reduced by up to 47% (10), although data for 2020 and 2021 also reflects the reduction in travel due to the pandemic.

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Working with our local stakeholders to improve air quality and health in London and beyond

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Introduction

This article outlines some of the ways by which the UK Health Security Agency's (UKHSA's) Radiation, Chemical and Environmental Hazards (RCE) Directorate are working with local stakeholders to support, inform and contribute to ensuring a more holistic, joined up approach to tackling air pollution.

Guidance documents for public health professionals – the City of London and London Boroughs

UKHSA supported the Greater London Authority (GLA) in producing updated 'Air Quality Guides for Public Health', aimed at increasing awareness and understanding of public health professionals of the causes and effects of air pollution in London. Published in February 2022, the Guides presume very little prior knowledge of air pollution and provide an overview of the key pollutants of concern in London and the associated health risks. These documents describe the latest evidence, outline the role public health professionals can play and presents a series of practical tools to help support further action on improving air quality and protecting the health of Londoners. They also signpost other useful resources and information. UKHSA and its predecessor organisation, Public Health England (PHE), made valuable and important contributions by providing information, advice, and support to help shape the content and ensure that it was appropriately targeted to meet the needs of public health professionals and maximise impact.

Matt Browning, Senior Policy and Programme Officer, Air Quality Team, GLA

"UKHSA and its predecessor organisation, PHE, played an important role in the development of the new Air Quality Guidance document for public health professionals. UKHSA provided valuable feedback on the layout, format and content of the document helping to ensure it lands with public health professionals and is a useful asset to boroughs. UKHSA's knowledge and experience was invaluable when updating the document and ensuring the most up to date public health studies and messaging is included to ensure consistency. Being able to consult with a public health expert throughout the development of the document has been incredibly helpful and enabled us to strike the balance between air quality and public health."

Borough-specific versions have been sent to the public health team in each of the London boroughs with the latest data to show the specific issues facing that borough within the context of London. This resource provides a practical means for local authorities to better understand the impacts of air pollution on the health of people in their area and what can be done to mitigate these effects locally. This is a timely resource which will help with needs assessment and to ensure that air quality is integrated into strategic decision making and relevant council plans and strategies.

London Air Quality and Health Delivery Group

A London Air Quality and Health Delivery Group has been established to provide the strategic leadership and aligned governance to ensure air quality is systematically considered as an important prerequisite for population health. It aims to drive forward pan-London joint work on air quality across the health and care system. The group is made up of representatives from: UKHSA, Office for Health Improvement and Disparities (OHID) London, GLA, Association of Directors of Public Health London (ADPH), London Environment Directors Network (LEDNet), NHS England and NHS Improvement London. This partnership is underpinned by a recognition that no single organisation working alone can effectively address London's air pollution and the related burden of disease. Rather than being constrained by organisational boundaries, this network brings together complimentary resources and knowledge to help drive forward the air quality commitments in the health and care vision for London.

Working together in this way offers a range of exciting opportunities to better align health and air quality agendas and to reduce fragmentation, overlap and duplication. It is important that UKHSA are part of these discussions to help ensure that environmental related actions are maximising the positive co-benefits to public health. Effective coordination is not just needed at the regional level, but across governmental levels; and UKHSA is uniquely positioned to help support and harmonize efforts across local, regional, and national levels.

Dr Tom Coffey, OBE, Mayoral Health Advisor, GLA

"The science is clear, air pollution kills. Action to improve the air we breathe is truly lifesaving and has never been more important. That's why we're bringing health and care partners in London together as part of our strategic action to improve air quality. The involvement of UKHSA has been a key part of our work in taking some of the boldest action in the world to tackle air pollution through our Ultra Low Emission Zone – which expanded in October 2021. UKHSA colleagues have supported us and our partners to understand and implement up-to-date scientific evidence in our joint air quality work and collated evidence of the detrimental impact of poor air quality on Londoners' health. They have also provided the invaluable connection to national policy developments in this area – helping to inform the work in London boroughs and support our action to ensure millions more Londoners breathe cleaner air."

On 17 February 2022, the Mayor of London convened a Clean Air and Health Summit to bring together leaders from across government and the health and care system. The summit called for more ambitious plans and accelerated action to reduce air pollution risks and health inequality. The summit concluded with 6 commitments across key action areas, including increasing public and professional awareness of air pollution and the health risks as well as actions that can be taken to reduce exposure. It was agreed that a newly established London Air Quality and Health Programme Office, hosted by UKHSA, would have ownership of tracking and coordinating the commitments from the Summit with relevant partners in London's health and care system. The Air Quality and Health Delivery Group will provide leadership to the Programme Office; and the Group recently submitted and secured funding from the London Health and Care Partnership to help support the work of the Programme Office.

London Air Quality Steering Group

The London Air Quality Steering Group, chaired by the City of London Corporation, is comprised of representatives from each of the London boroughs' air quality cluster groups (central, north, south, east, and west), the Environment Agency, GLA, UKHSA and London Councils. The role of this group is to share knowledge, expertise, and best practice, and seek joint solutions to shared pollution problems. Engagement in this group increased the visibility of the work UKHSA does on air quality.

Mr Nick Marks, Pollution Control Officer, Newham Council, representative of the East London Cluster Group

"I have found the presence of UKHSA, at the cluster coordinators meeting a valuable insight into the work of the organisation in promoting clean air. It has also enabled me to pass key information to my colleagues working in air quality in the East London area."

Moreover, it has helped UKHSA understand more clearly the issues, concerns, and ideas of local authorities. Keeping open lines of communication between local teams and UKHSA's national Air Quality and Public Health group has also enabled an effective information and knowledge flow between local, regional, and national teams.

Ms Kyri Eleftheriou-Vaus, City of London Corporation, London Air Quality Steering Group Chair

"The presence of UKHSA at the London Air Quality Steering Group is a welcome addition to the membership. UKHSA's involvement has been beneficial in increasing local authorities' awareness of UKHSA's work on the health impact of air pollution and providing a point of contact. UKHSA's attendance also supports the exchange of information to UKHSA on the varied projects and awareness raising activities being undertaken by local authorities to improve air quality at a London wide level."

Engaging with our internal stakeholders

Measures to tackle air pollution offer unique opportunities to benefit other public health strategic priorities, such as obesity, as well as also helping to reduce health inequalities. Over the years, RCE had established strong links with former PHE London Health Improvement colleagues and Health Protection Teams (HPTs). Fostering these strong relationships has been incredibly beneficial in facilitating the development of shared goals and the coordination of action.

RCE continues to provide expert support and input into a number of documents to ensure that the information is relevant and accurately reflects the most up to date scientific evidence. Prime examples include input into Health and Wellbeing needs assessments on air quality and high-level briefings for Professor Kevin Fenton (Regional Director for London, OHID) and Dr Tom Coffey (Mayoral Health Advisor, GLA). Engaging regularly with UKHSA's national Air Quality and Public Health group has helped to facilitate the flow of information, advice, and guidance between relevant local, regional, and national teams. Having established these positive and effective working relationships has also ensured that this cross-organisation working has been sustained with the transition of PHE's health protection and improvement functions to UKHSA and OHID, respectively.

Julie Billett, Deputy Director, Operations, Office for Health Improvement and Disparities, London

"Improving the quality of London's air, and reducing and preventing the impacts of poor air quality on Londoners' health, is a key strategic priority for health and care partners. UKHSA's Environmental Hazards and Emergencies Department is a key partner in London's collaborative work on this agenda, bringing much valued technical expertise, specialist advice and experience, and helping broker important connections both regionally and nationally, all of which has helped London make positive progress. Following changes to the public health system in 2021, this spirit of collaboration across organisational boundaries and a shared commitment to the pursuit of aligned priorities is valued more than ever."

Regional working across systems to improve air quality and health

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Introduction

Public health systems within regions support the delivery of better public health outcomes. This is done by providing leadership, influence, professional development support and undertaking collaborative work programmes contributing to positive health impacts and collective advocacy work for key public health priorities (1).

Improving air quality and public health outcomes at the population level is complex. It involves cross sector actions owned by different departments or teams and embedded within regulatory, health or guidance frameworks. In this article we call this 'parts of a system'. For maximum population public health gain, we need these parts of a system to align into a whole system approach for improving health outcomes.

This article discusses 4 recent work activities building towards a whole systems approach to improve air quality and health outcomes in the Yorkshire and Humber Region. These activities could be readily replicated in other regions. These are:

- establishing challenges and needs through a regional survey
- raising awareness and upskilling the health workforce
- improving access to data on health and air quality
- developing a framework for a whole system approach

Establishing challenges and needs through a regional survey

In 2019, the Public Health England (PHE, now UKHSA) Yorkshire and Humber Health Protection Team interviewed their local authorities (environmental health and public health teams) to explore challenges when tackling air quality to improve public health outcomes. Needs were grouped according to how PHE could best support them. Five key themes emerged, which are:

- development and sharing of evidence on health harms of outdoor air pollution
    - summarising evidence on different sources of pollution and different contexts (such as rural, urban, agricultural, coastal)

  - support with local area data (such as mortality, vulnerable populations, health profiles)

- sharing information on effective interventions
  - sharing case studies
  - support for evaluation (design and implementation)
  - evidence on controversial interventions (such as green walling, idling)
  - tailored materials on intervention for partner organisations
  - improved understanding of local progress

- support for communication and awareness raising
  - clear messages on economic development and clean air
  - support to tackle disinformation
  - a national campaign or support for regional campaigns
  - a set of clear, consistent messages
  - support on behaviour change and community engagement
  - positively framed messages
  - messaging for health professionals
  - an air quality and health website
  - non-technical materials and frequently asked questions
  - messaging on links with climate change
  - messaging on links with other public health topics

- facilitation of collaboration
  - engagement with existing groups across the region
  - a focus on air quality in other public health groups (such as those working on communities of improvement, active travel)

- other suggestions
  - closer connection between universities and public health
  - key health and air quality contacts in PHE (now UKHSA)
  - support for local projects and funding applications
  - national cross-government advocacy

The survey feedback within the region was essential to establish local priorities and inform a public health work programme focused on addressing barriers to system-wide action to improve air quality and health (2).

Raising awareness and upskilling the workforce

Building on the survey results and capitalising on the annual Global Action Plan Clean Air Day, PHE and the Yorkshire and Humber Public Health Network held a ‘Cleaner Air, Better Health Webinar’ in May 2021 (3). Its aims were to:

- support Global Action Plan and partners in Clean Air Day 2021
- raise awareness of the public health impacts of poor air quality
- share the latest evidence and health indicators on the public health impact of air pollution
- bring key stakeholders together in Yorkshire and Humber to start a conversation on future collaboration to improve air quality and health outcomes
- explore how local public health teams can support interventions to improve air quality

Attendance and content

PHE was supported by the Association of Directors of Public Health (ADPH) (Yorkshire and Humber Network) and the Yorkshire and Lincolnshire Pollution Advisory Group (YALPAG), a regional environmental health network. Over 100 delegates attended from a wide range of disciplines and sectors, encompassing environmental and public health leads from all the region's local authorities, active travel leads, transport planners, spatial planners, clinicians, the Environment Agency, academics, and community organisations such as Global Action Plan, Living Streets (Leeds) and Yorkshire Sport.

Speakers from different public health disciplines addressed sources of air pollution, evidence of health harms, interventions that could be taken to improve air quality and health, health indicators, and collaborative approaches to action to improve health. Interactive surveys were used to obtain delegate feedback.

Outcomes from the webinar

There was consensus among delegates that the wider public health workforce and primary healthcare have a role in improving air quality and associated health outcomes. The role and responsibilities of health professionals in supporting improved health outcomes could be explored further at local, sub regional and regional tiers. There was support for a regional framework for a whole systems approach to improving indoor and outdoor air quality and positively influencing public health outcomes. This would involve public health professionals' collaboration with local authorities, combined authorities, mayoral regions, integrated care systems, healthcare, and other organisations. Indoor air quality was addressed in more detail at a subsequent regional 'Homes and Health' webinar in 2022, where UKHSA presented on the health impacts of residential indoor air quality (4).

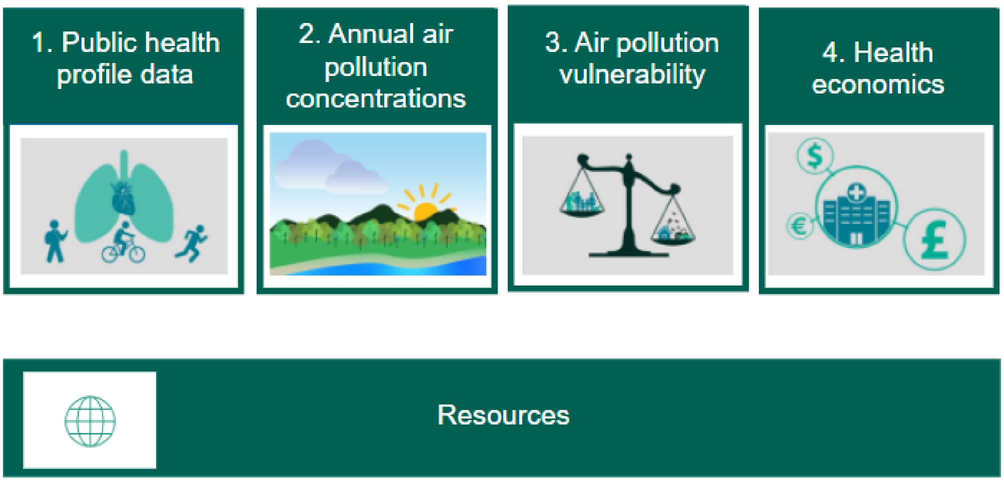
Development of an Air Quality Health Indicator tool

Access to air quality and health outcome data informs the development of air quality strategies, and design and evaluation of interventions to improve local air quality and improve health. Stakeholders across the Yorkshire and Humber indicated that there was local demand for health indicators and related support.

Within the region, an air quality health indicator tool is under development which collates modelled air quality concentration data and health indicators to highlight population vulnerabilities and health impacts. This is a collaboration between the Yorkshire and Humber Office for Health Improvement and Disparities (OHID) local knowledge and intelligence service (LKIS), OHID health and wellbeing (HWB) teams and UKHSA environmental hazards and emergencies department. The tool incorporates 4 themes (Figure 1):

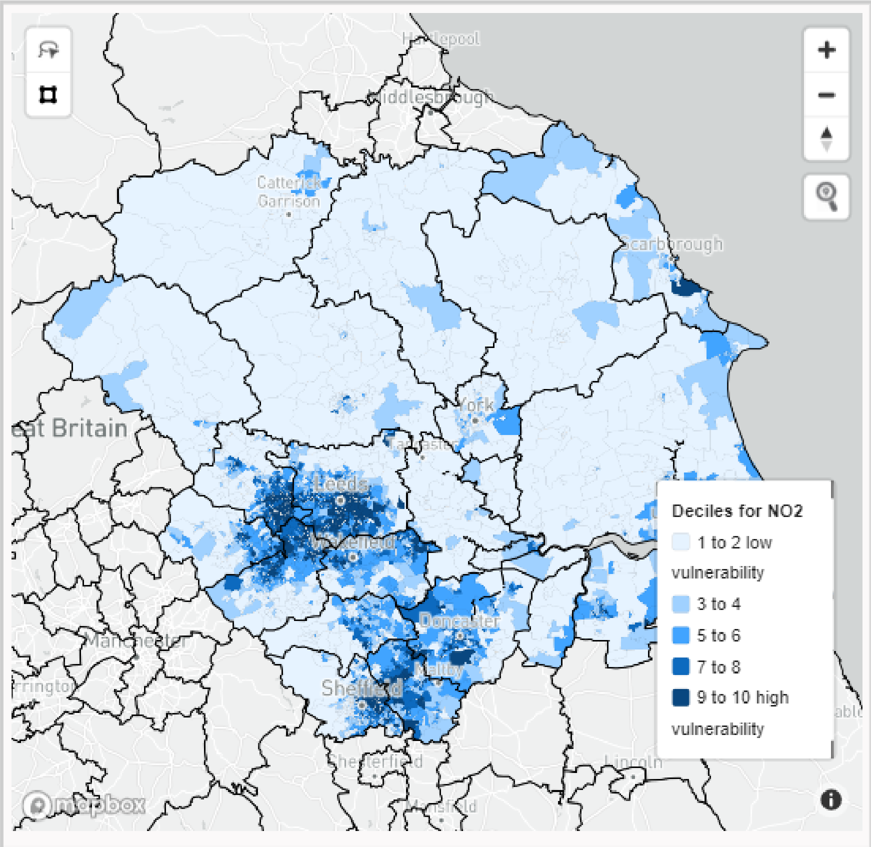
1. public health profile data from the Public Health Outcomes Framework (PHOF) and related Office for National Statistics (ONS), Natural England and National Travel Survey data sets
2. air pollution concentration indicators from Defra that are compared to World Health Organization (WHO) Air Quality Guidelines
3. a pilot UKHSA air pollution vulnerability indicator to identify populations vulnerable to air pollution
4. information on health economics, namely cost savings associated with reductions in air pollution

Figure 1. The proposed contents of the Air Quality Health Indicator Tool



The tool focuses on local authorities' areas and allows comparison of Defra-modelled air pollutant concentration data with health standards and guidelines such as WHO air quality guideline values, and it includes an air pollution vulnerability composite indicator developed by a UKHSA environmental epidemiology working group (described in detail by an article in this issue). This pilot indicator is under consultation and is available at Lower Layer Super Output Area (LSOA) level for all local authorities in England. Figure 2 shows vulnerability from nitrogen dioxide in Yorkshire and the Humber, where 16.4% of the regional population are in the most vulnerable Lower Super Output Area deciles 9 and 10 (901,000 people). Darker blue deciles are used to show populations in LSOA that are more vulnerable to nitrogen dioxide.

Figure 2. Pilot air pollution vulnerability indicator for nitrogen dioxide in Yorkshire and Humber



Population level vulnerability to air pollution (Pilot)

Nitrogen Dioxide (NO^2)

For vulnerability from nitrogen dioxide in Yorkshire and the Humber, 16.4% of the regional population are in the most vulnerable Lower Super Output Area deciles 9 and 10 (901,000 people)

Source: UKHSA Air Pollution Exposure Surveillance System, April 2022

Taking a whole-systems approach to air quality and health

The population and individual health impacts associated with exposure to air pollution are increasingly well evidenced, emphasising the importance of raising awareness, supporting interventions, and communicating health messages to our most vulnerable populations. Many organisations have a role in addressing sources of, exposures to, and health outcomes arising from air pollution. The challenge for health professionals is to lead action to improve air quality and health across the whole system, local, sub-regional and regional tiers of government, across organisations, and within communities and places. By bringing parts of the system together for leadership and collaboration as a whole-system, there are benefits, which are described in Figure 3 (which is adapted for air quality from PHE's 'Whole Systems Approach to Obesity' (5)).

Figure 3. The potential benefits of recognising the bigger picture and taking a whole-system approach

The benefits of a whole-system approach

1. Effect of collective actions is greater than the sum of the individual actions – identifies, implements, and aligns actions that have wider impact across the local system

2. Reflects the local leadership role of local authorities – enables reach and penetration into local places, working with and through an extensive range of stakeholders, including communities and healthcare providers

3. Aligns with a 'Health in All Policies' approach – recognises the range and complexity of air quality issues to support a system-wide approach to consider and address them in policies and plans

4. Maximises all the assets in the local area, including community assets – recognises and identifies local assets to help build on the particular strengths of local communities

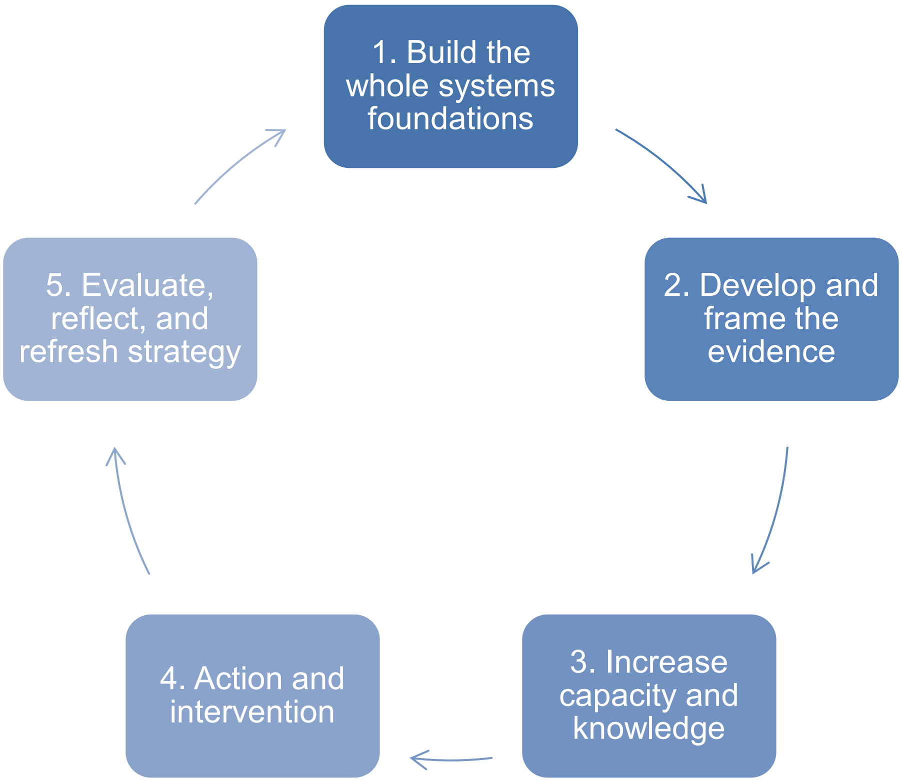
5. Supports a community-centred approach to tackling health inequalities – involving local communities, in particular disadvantaged groups, to better reflect local realities, help improve health and wellbeing and reduce health inequalities

6. Develops transferable workforce skills and capacity – relevant and applicable to other complex issues

7. Recognises the potential of all partners to contribute – involves NHS organisations, local authority departments and the education, business, and voluntary sectors to improve the population's health

A 5-step approach characterised work in the Yorkshire and Humber region towards a whole system approach: building the whole systems foundations; developing and framing evidence; increasing capacity and knowledge; action and intervention; and evaluating, reflecting, and refreshing strategies (Figure 4). The whole system principles and approach can be applied at community and place, local authority, sub-regional or regional levels. As the system changes at each level, applying it at each tier brings different opportunities for collaboration, network, and interventions to improve air quality and health.

Figure 4. Steps to implement a whole systems approach to improve air quality and health



Lessons learnt and recommendations

Whilst locally led work programmes will differ due to local needs and priorities, the programme of work to improve air quality and health across Yorkshire and Humber has generated useful insights other local leads on air quality and public health can apply in their own work. For others looking to take similar approaches, the author's personal recommendations are to:

- understand the role of public health and needs in your locality in relation to both outdoor and indoor air pollution
- use consultations, events, and discussions to involve stakeholders and find shared opportunities to improve local health outcomes
- raise awareness of existing air quality and health indicators with stakeholders and decision-makers
- as there is no one-size-fits-all approach, use the collaborative principles of the whole-systems approach to build and adapt systems leadership and work programmes to local circumstances

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Air quality and health: UKHSA's operational role

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Introduction

The UK Health Security Agency (UKHSA) carries out public health risk assessments and provides public health advice as part of the multi-agency preparedness and response to environmental hazards and emergencies. This article outlines 3 types of event that affect day-to-day air quality and UKHSA's operational role. Fires involving our natural or built environments can lead to localised impacts on air quality. In other cases, wider areas can be affected by short-term episodes of poor air pollution due to traffic and industrial emissions, transboundary pollution, weather conditions or atmospheric chemistry. Short-term exposure (over hours or days) to elevated levels of air pollution can also cause a range of health impacts, including effects on lung function, exacerbation of asthma, increases in respiratory and cardiovascular hospital admissions and mortality.

Ambient air pollution episodes

Ambient air pollution episodes (short-term episodes of poor air quality) routinely occur across the UK, particularly during spring and summer. Such episodes are forecast by the Met Office, who post updates on Defra's UK Air website. The Defra Daily Air Quality Index (DAQI) categorises air pollution as 'Low', 'Moderate', 'High', or 'Very High', based on the highest of any one of the main outdoor air pollutants (nitrogen dioxide, sulphur dioxide, ozone, 'fine' particles equal or less than 2.5µm in diameter ($PM_{2.5}$), and 'coarse' particles between 2.5 and 10µm in diameter (PM_{10})).

Warnings are generally issued when a 'High' or 'Very High' air pollution episode is forecast or 'High' or 'Very High' levels are measured for several days or over a large part of the country. Defra is the lead government department and notifies stakeholders – which include the UKHSA, Met Office and Devolved Administrations – and coordinates information sharing and public communications.

UKHSA helps to disseminate health messages prior to, and during, episodes to raise public awareness and ensure people are aware of actions they can take to protect their health. This involves its environmental public health scientists, health protection teams, and communications leads. UKHSA and partner organisations amplify social media messages published by Defra and support national communications activities; UKHSA representatives also participate in national or local media interviews and locally led communications. More information about the provision of information on the health impacts of air pollution and the DAQI can be found in a complementary article in this issue.

Wildfires

A wildfire is defined as any uncontrolled fire involving grassland, moorland, heather, woodland, forests, gorse or other vegetation and any inflammable underlying substrate (such as peat-rich soils). The UK Climate Change Risk Assessment cited wildfires amongst the top 10 risks to the natural environment in England (1) and the UK's National Risk Register assessed large-scale wildfires to be as a 'medium' risk (in terms of severity and likelihood of occurrence) (2). Between April 2006 and March 2017, Fire and Rescue Services in England attended nearly 260,000 wildfires (approximately 32,000 per year) (3).

Wildfire smoke from burning vegetation and wood can contain large amounts of fine and ultra-fine particles (4). Harmful gases include carbon monoxide and nitrogen oxides, as well as carcinogens such as polycyclic aromatic hydrocarbons (which may also be present on or within particulate matter), aldehydes, and volatile organic compounds, including benzene (5, 6). Large-scale wildfires can generate secondary pollutants, such as ozone, which are potentially hazardous to public health.

Wildfire incidents around the world have led to exceedances of the health-based air quality standards that are used to identify exposures of potential concern. There is strong epidemiological evidence that exposure to smoke from large-scale wildfires can lead to respiratory effects, and increased hospital admissions, primary care consultations and prescribing of medications (7, 8). Exposures have also been linked to cardiovascular symptoms (9). Individuals at greater risk of health effects from exposure to wildfire smoke include those with pre-existing respiratory and cardiovascular diseases; middle-aged and older adults; children; and pregnant women and the foetus (7).

Fires

Approximately two-thirds of the incidents notified to UKHSA's national duty desk and out-of-hours chemical hotline involve fires. Sources vary from buildings to chemical and fuel stores, agricultural products such as hay and straw, and stockpiles of materials or waste. In common with wildfires, risks to public health primarily depend on the concentration and duration of exposure to products of combustion, which are reviewed in past UKHSA publications (10, 11). Additional risks and hazards include physical hazards associated with thermal radiation and explosions, spills and firewater runoff, and downwind deposition of debris that may include asbestos-containing-materials.

Prolonged smouldering fires can pose challenges for the multi-agency response and public health risk assessment because it is not possible to shelter indoors indefinitely. In such cases, risk assessments and advice to the public must be reviewed on a regular basis (12). Multi-agency communications may need to include additional advice about current and forecast weather conditions, identifying which areas nearby are at higher risk and which areas are likely to be unaffected.

Exposure, risk assessment and public advice during fires

UKHSA specialists carry out dynamic public health risk assessments throughout incidents and events. There is a network of fixed real-time air monitoring stations in England, which are generally located close to industry and in urban areas. Their data is made available through Defra or local authorities. Initial assessments of people's exposure to air pollution are informed by information from partner organisations, forecasts generated by computer models, and any relevant measurements from the ambient air monitoring network. Concentrations are compared to health-based standards and guidelines such as the UK DAQI bandings.

When chemical incidents and fires (including wildfires) pose potentially significant risks to public health, an Air Quality Cell (AQC) may be convened. This is a multi-agency group whose core members are the Environment Agency and chemical specialists from UKHSA. The AQC carries out risk assessments and, if criteria for deployment are met, can mobilise air quality monitoring teams to the local area at risk.

During emergencies exposure assessment is informed by regular feedback from emergency responders at the scene of incidents, current and forecast meteorological conditions (available to responders via the Met Office's Hazard Manager service), specialist 'CHEMET' forecasts of plume dispersion, air quality monitoring, and syndromic surveillance carried out by UKHSA or ad-hoc by health partners. Public health advice is typically to "go in, stay in, and tune in" to minimise exposure to airborne hazards until they have passed.

During prolonged episodes of poor air quality, each of the UK DAQI bandings is associated with risk-based health advice that can be used to provide day-to-day advice to the public and vulnerable groups. The UKHSA typically provides written advice to partner organisations that is disseminated via press releases, traditional media, social media, and partners' websites and wider communications activities.

UKHSA has also developed resources to support the preparedness for fires and short-term episodes of poor air quality. These range from factsheets and advice for medical and other professionals, and protocols for local health surveillance, to arrangements for supporting local authorities when they lead on extended air quality monitoring and long-term communications activities during prolonged incidents or in the recovery phase after an incident has occurred.

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Theme 3: Improving awareness and understanding

Improving awareness and understanding

Addressing the air pollution problem requires awareness and understanding among everyone from national and local government, health professionals to the general public. While awareness has improved, more needs to be done. In 2021 an inquest into the death of Ella Adoo Kissi-Debrah following an asthma attack found that air pollution "made a material contribution" to her death. The coroner's report (1) highlighted that:

> "There is a low public awareness of the sources of information (such as [the] UK-Air website) about national and local pollution levels. Greater awareness would help individuals reduce their personal exposure to air pollution… The adverse effects of air pollution on health are not being sufficiently communicated to patients and their carers by medical and nursing professionals."

Through its Cleaner Air Programme, the UKHSA works to improve understanding of the effects of indoor and outdoor air pollutants on health by developing actionable information and advice.

Raising awareness with health care professionals

To raise awareness and increase the confidence and skills of health care professionals to address air pollution in their day-to-day practice, UKHSA has published an 'All Our Health' training module on air pollution and health. This is accompanied by an e-learning resource, and was developed with Health Education England (2). Figure 1 shows a screenshot of the landing page with prompts to learn "Why does this matter?" "What can I do to help?" and "Where can I find more information?"

Figure 1. All Our Health: Air Pollution e-learning content for health and care professionals

The AQPH team has also published articles to raise awareness of the impacts of air pollution on health among different medical professionals. An article entitled 'Why air pollution is an important issue for all nurses' (3) co-authored with Prof. Jamie Waterall, Deputy Chief Nurse for England, in the British Journal of Nursing, describes the essential role that nurses can play in helping to protect patients from the impacts of air pollution. In this issue, Larissa Lockwood from Global Action Plan outlines why 'Health professionals are vital in the battle against air pollution'.

We work with the NHS, for example on their 'National bundle of care for children and young people with asthma' (4), which includes guidance around environmental impacts to support integrated care systems to deliver high quality asthma care. UKHSA is also consulting nurses, doctors and other health professionals regarding updates to health advice associated with pollutant bandings in the Daily Air Quality Index, focussing on how people with asthma can modify behaviours to reduce health risks during air pollution episodes.

Raising awareness with the public and other stakeholders

UKHSA is working on a wide review of air quality information systems (described in more detail in an article in this issue), alongside the Department for Food and Rural Affairs (Defra) and Department of Health and Social Care (DHSC). This forms part of central government's response to matters of concern highlighted in the 'Ella Adoo Kissi-Debrah: Prevention of future deaths report'.

We support Global Action Plan with Clean Air Day: staff across UKHSA undertake various activities to help raise the profile of Clean Air Day and encourage stakeholders, colleagues, and their own families to take action to reduce sources of air pollution and their exposure.

We also attend public outreach events such as 'New Scientist Live' and the 'ATOM Science and Technology festival', Oxfordshire. For schoolchildren, we have worked with the WHO to produce an educational tool for schools on chemical pollution of indoor air and its risk to children's health (5). We also supported Canterbury City Council and the MIDKENT Environmental Health Partnership with their digital resource for primary schools, described by Kelly Haynes in an article in this issue.

To reach a wider audience of environmental professionals, UKHSA contributed a feature article to the 'Improving Indoor Air Quality' issue of Environmental Scientist, the journal of the Institute of Environmental Sciences (6). This discussed the UKHSA's role developing evidence of the health impacts of indoor air quality, identifying potential interventions to reduce harms, and influencing decision-makers and the public in order to improve health outcomes.

Having a better understanding of exposure to air pollution and where the most vulnerable populations are is important for helping to raise local awareness of the problem. We discuss UKHSA's work on health surveillance and mapping air pollution in the concluding article in this section.

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Health professionals are vital in the battle against air pollution

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Global Action Plan is an environmental charity working towards a green and thriving planet where everyone can enjoy happy and healthy lives within the Earth's limits. We tackle the root causes of our climate and nature crises through research, campaigns and collective action that reconnect human and planetary health.

Introduction

In January 2021, legal history was made when a coroner ruled that air pollution was a cause of the death of 9-year-old Ella Kissi-Debrah. This followed a brave campaign led by her mother, Rosamund Kissi-Debrah, to ensure justice for Ella. In the subsequent 'Prevention of Future Deaths Report' shared by the coroner, one of the key recommendations was a call for health professionals in the UK to be trained and talking to patients about air pollution (1).

Every year, air pollution causes up to 36,000 deaths in the UK (2) and at least 4 million early deaths globally (3). Poor air quality causes heart and lung diseases, is linked to low birth weight and children's lung development, and may even contribute to mental health issues.

With the World Health Organization (WHO) and the UK Government recognising that air pollution is the "largest environmental health risk we face today", you would not be wrong to presume that the health sector plays a critical role in responding to air pollution. Unfortunately, this is currently not the case.

As a sustainability charity, here at Global Action Plan we are working to change this and believe air pollution requires a concerted action across public health and frontline healthcare services.

We believe this because of:

- educators – health professionals, as trusted messengers in society, play an important role to inform the public of the health risks from air pollution
- role models – the health sector can show leadership by minimising the air pollution the NHS creates and influences
- champions – the health sector can play a vital role in supporting policy measures at national and local levels that will help ensure improvements to air quality

There are many keen champions across the health service actively working on air pollution, but they are in the minority. We have been working with a number of these champions on projects to help accelerate action on air pollution across the health sector.

Educators – Mobilising Health Professionals demonstrator projects

Global Action Plan is working to help ensure health professionals in primary and secondary care are trained to advise patients on the impacts of air pollution and how to protect their health.

The serious gap in current medical training highlighted in the Prevention of Future Deaths Report was a concern that previously came to light through our Mobilising Health Professionals project in partnership with the UK Health Alliance on Climate Change (UKHACC) (4).

Throughout 2020 we worked with 40 respiratory and paediatric health professionals to train the group on the impacts of air pollution on patient health and the measures people can take to reduce their exposure to this hazard. While health professionals already provide health advice around lots of lifestyle issues including smoking, exercise and diet, health professionals reported that:

- they are not talking to or advising patients about air pollution
- air pollution is not uniformly integrated into healthcare professional training
- materials are not readily available for health professionals to share with their patients on air pollution

Harnessing this insight, we worked with these 40 health professionals to understand what types of materials and resources would be most useful to share with patients on air pollution, and where in the patient pathway conversations could be best held. As a result of the project a selection of leaflets and posters are now available for colleagues across the health sector to use (5).

We are also running a new pilot project with GPs and are looking for GP Clean Air Champions to take part in a project to incorporate air pollution advice into the patient pathway. The aim of the project is to understand the best ways to engage with patients about the health risks of air pollution and actions to protect their health. Engaging GPs in the air quality agenda will in turn enable them to deliver messages to vulnerable individuals. The learnings from the pilot will be used to expand the project nationwide.

Role models – Clean Air Hospital Framework

As an organisation, we also help hospitals to respond to air pollution in and around the hospital, as well as surrounding communities, through free initiatives such as the Clean Air Hospital Framework (6). The Framework enables health professionals to set ambitions and self-assess progress on tackling air pollution in 7 key areas: travel, procurement and supply chain, construction, energy, local air quality, communication and training, and hospital outreach and leadership.

We partnered with Great Ormond Street Hospital (GOSH) to develop this framework, which enabled GOSH to launch the first ever hospital clean air strategy. Using the framework, air quality has since been built into GOSH's new building developments, both within building design and during construction activities. The new buildings are designed to emphasise green spaces, use low polluting materials, and incorporate energy efficiency measures to reduce local fossil fuel energy generation. On the construction site ‘no idling’ messaging is provided to all vehicles arriving at the site, dust levels are monitored, and deliveries are restricted as much as possible.

Around the hospital, there are also now signs discouraging idling that have been co-created with patients. Play specialists and play workers have been engaging with children on clean air, including designing their own clean air superheroes, and a Young People's Forum have been sharing why they think it is important for hospitals to take action on air quality.

Going forward, GOSH is further embedding clean air requirements within new contracts and tenders, bringing clean air messaging into the GOSH school, training staff, reviewing cleaning products, and continuing to encourage other hospitals to take more action to make the air cleaner for everyone. The case study has enabled peer-to-peer learning opportunities with GOSH to help other hospitals across the UK to tackle similar barriers.

Champions – Clean Air Health Sector Summit

While resources, materials and education help to arm the health sector in the battle against air pollution, this alone is not sufficient for mass adoption and action. UK leaders still need to implement a nationwide programme to support the inclusion and integration of air pollution into patient advice and health sector practice at a top-level, as per the coroner’s guidance in the ‘Prevention of Future Deaths Report’.

To help achieve this, Global Action Plan works with national bodies and local authorities to promote collaboration across the public sector to increase awareness and encourage action on air pollution. An example of this was the Clean Air Health Sector Summit that was held ahead of Clean Air Day 2020 (7). The Summit brought together decision-makers across the health sector to discuss and agree the action needed from the sector to tackle air pollution.

The event resulted in 17 immediate opportunities that were identified across the following 4 areas:

- reducing emissions – reducing patient travel, supply chain innovation, setting targets for management, and incorporating clean air in the NHS Net Zero Plan (8)
- advising patients – updating healthcare professionals' practices, providing educational materials for patients in health centres, launching a national public health campaign
- education – raising understanding of air quality inequalities and the need to protect those most at risk of health issues caused by pollution
- collating experiences to influence policy – sharing the real and personal impacts that air pollution is having on patients to ensure the need for comprehensive and urgent action is understood across the political spectrum across the country

Clean air in and around healthcare settings is crucial for the most vulnerable, but no one should have to breathe dirty air. By improving the air quality in healthcare environments, the positive impacts will go beyond the boundaries of the hospital, clinic room or GP practice. For more information on our work with the health sector and health professionals, head to our website (9).

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Pollution patrol: A digital resource for primary schools

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Project overview

Canterbury City Council and the MIDKENT Environmental Health Partnership were awarded Defra air quality grant funding in March 2021 to develop a digital resource for primary schools to educate children aged 5 to 11 years and their parents about air pollution. The UK Health Security Agency (UKHSA) was invited to be involved in the project from the start to give guidance on the health impacts of air pollution and gave valuable feedback during the development process.

The aim was to create a resource to raise awareness of the causes and harmful effects of air pollution through fun, engaging and practical strategies that:

- support schools and teachers in promoting less polluting travel behaviour
- educate and empower children to act as advocates and ambassadors for reducing air pollution in school and at home
- provide a framework for discussion between children and their families to talk about air quality and health

The Pollution Patrol[1] website (1) was launched on 25 April 2022 and is available to 537 primary schools and more than 150,000 children and their parents across Kent and Medway. Figure 1 is a screenshot showing the Pollution Patrol characters.

Figure 1. Pollution Patrol characters

Pollution Patrol is brought to life using an immersive animated story which allows children to journey through the fictional town of Sooting where they meet the narrator Aireal, a floating cloud of air, and the Pollution Patrol gang. Aireal invites the children to play games to learn where air pollution comes from, what it is made up of, how it can affect our health and ways to reduce it in and around schools and at home. Pollution Patrol can also be accessed by children and their parents at home to ensure key messages are transferred and that behaviour change is encouraged.

The website encourages a sustainable change in children and their parents' habits by educating them about the causes and harmful impact of air pollution and encourages them to take action to protect their health and reduce their own negative impacts. As children and parents use the website, we expect their understanding and awareness of the issues around pollution and air quality will be improved, motivating them to change their behaviours in ways which we hope will stay with them for life.

Background

The initial plan, formed after teaching children about air pollution in classrooms and school assemblies, was to create an air pollution digital information pack to give to schools. In April 2020, during lockdown learning, children were given free access to websites such as 'The Maths Factor' and 'BBC Bitesize' (2, 3). These tools enabled children to show their parents what they were learning and to teach them how to play games and earn rewards. This led to the idea of creating an all-encompassing digital resource to reach a wide audience of teachers, children, parents, relatives, and friends to raise awareness and to encourage behaviour change.

A search of the internet led to finding the hugely successful Move It Boom programme which was a digital campaign run by Leicestershire Partnership NHS Trust to inspire children to get more physically active (4). The programme first ran in 2013 where 218 primary schools took part in a region-wide challenge and 47,0000 activities were logged in the first 5 months.

Project brief

The objectives of the project were to:

- create content for all 3 key audiences – children aged 5 to 11 years, children and their parents and primary school teachers offering practical strategies and solutions to reduce their impact on air pollution, firstly, in relation to travel to, from and around schools, but also in the wider community
- support schools and teachers in promoting less-polluting travel behaviours to and from school and around school grounds
- educate children and give them the resources to encourage them to act as advocates and become ambassadors for reducing air pollution in school and at home
- encourage discussion between children and parents and other family members regarding air pollution and ways that it can be reduced
- educate, inform, and influence, without shame or blame, being aware of the different routes and means by which children travel to school and how much control they have in this area

Solution

The result was to create a multi-platform digital resource comprising:

- website with sections for teachers, parents, and pupils
- immersive 360° animated story – a journey around the fictional town of Sooting where pupils can help the Pollution Patrol improve air quality by searching for hazards
- interactive games on what air pollution is, where it comes from, health effects, routes to schools and pollution in the home
- downloadable teaching resources including an assembly plan, curriculum-linked lesson plans and pupil activities devised for Key Stage 1 and 2 pupils

Pollution Patrol is introduced to children and parents through an assembly, including a play script so that pupils can take on roles of the Pollution Patrol. The assembly finishes with the Pollution Patrol Song (to the tune of 'What shall we do with the drunken sailor') to reinforce the key messages which are reintroduced as part of curriculum-linked lesson activities for each key stage.

The website also houses branded activity plans, a teachers' guide, an assembly plan and play script to help teachers in introducing the theme of air pollution and air quality across all target demographics (students, teachers and parents and carers). The website also has a pledge wall where schools can upload pictures of what their classes have been doing and the pledges they've made to make changes to reduce air pollution, such as walking to school more often.

Inclusion was an important part of the design process. To ensure everyone felt they were represented within the resource, a range of diverse supporting characters was created to reflect a range of ethnic and cultural backgrounds, as well as to reflect disabled people and wheelchair users. Using the characters and digital assets from the animation, further games, quizzes, collectable badges, and other materials have been created.

Getting the message into the home is an important element of the project, so all pupils at registered schools receive a take-home leaflet, which will allow for messaging to be transferred and shows parents and the wider family how to access the website and the interactives to learn more about air pollution.

Measurement, evaluation, and adaptation

The website, interactives and teaching resources were piloted by 2 schools in Sittingbourne in February 2022. Feedback received was very positive. The children loved the animation and characters and the teachers said that the quality of the resources was excellent and enjoyed using them in class. Website analytics will provide future data on user interaction with digital content and downloads and reports will be provided on enrolment, progress, and performance. Further quantitative and qualitative evaluation of the resource will also take place using periodic online surveys to continually evaluate the effectiveness and refine the resource.

Dr Sarah Hotham, Senior Research Fellow and BPS Chartered Psychologist at the Centre for Health Services Studies at the University of Kent, will be undertaking a robust evaluation to judge the impact and implementation of the resource after 6 months of it being used in schools. We expect schools to begin fully implementing the resource in classrooms in September 2022 and for the evaluation to be undertaken in March 2023.

Lessons learnt

What went well?

From the start of the project a collaborative approach was employed, ensuring opportunities for contribution from health awareness partners, the UKHSA and evaluation partners. The Centre for Health Services Studies at the University of Kent facilitated at key points in the development of the project.

The teaching resources were created in collaboration with a network of practising teachers to ensure that the content was curriculum-linked, and the tone and visual style allowed for the breadth of age and maturity among primary school children. We achieved this by being appealing and relatable to children at the upper end of the primary sector as well as accessible and understood by younger children.

To ensure the new website gained maximum visibility, a comprehensive communications plan and messaging matrix, providing rich editorial content, social media, traditional and electronic direct mail for schools, and internal communication pieces was developed. This was used to support the launch and will be valuable for future promotional activities of the Pollution Patrol.

The launch webinar was attended by air quality specialists, senior managers, councillors, and key stakeholders. Below are a few quotes from the launch:

The Lord Mayor of Canterbury, Councillor Pat Todd

"You're on to a winner here with these innovative resources! Enthused and informed children are a great way to influence their parents to positive behaviour changes."

Delainey Curry, Scientific Officer at Tunbridge Wells Borough Council

"I've worked in teaching previously and just want to say the quality of these materials are really, really phenomenal, I'm so excited to see how things continue with this project."

Simon Krafft, Head of School at Newington CEP School

"Learning outcomes and activities mirror what we are learning in school, and it gives the children 'Oh okay' moments that mean they learnt something new."

The Defra air quality grant manager was very impressed with the website and advised that a case study could be shared on the online knowledge sharing resource the Air Quality Hub (5) and that it had potential to be used nationally.

Areas for improvement

The initial aim was to undertake a pilot with 2 schools from each of the 4 authorities involved in the development of the project. Recruitment of pilot schools proved to be extremely difficult due to the after-effects of the coronavirus (COVID-19) pandemic, as only 2 schools were able to sign up to pilot the resource. One way to overcome this would have been to offer to visit the schools to deliver the school assembly. Future applications for grant funding will include contingencies for staff resources to overcome similar issues.

Acknowledgements

The author would like to thank Stuart Maxwell of the MIDKENT Environmental Health Partnership, Alannah Moore, and Racheal Fudge from TMC Strategic Communications for providing helpful comments in the preparation of this article.

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Air Quality Information System Review

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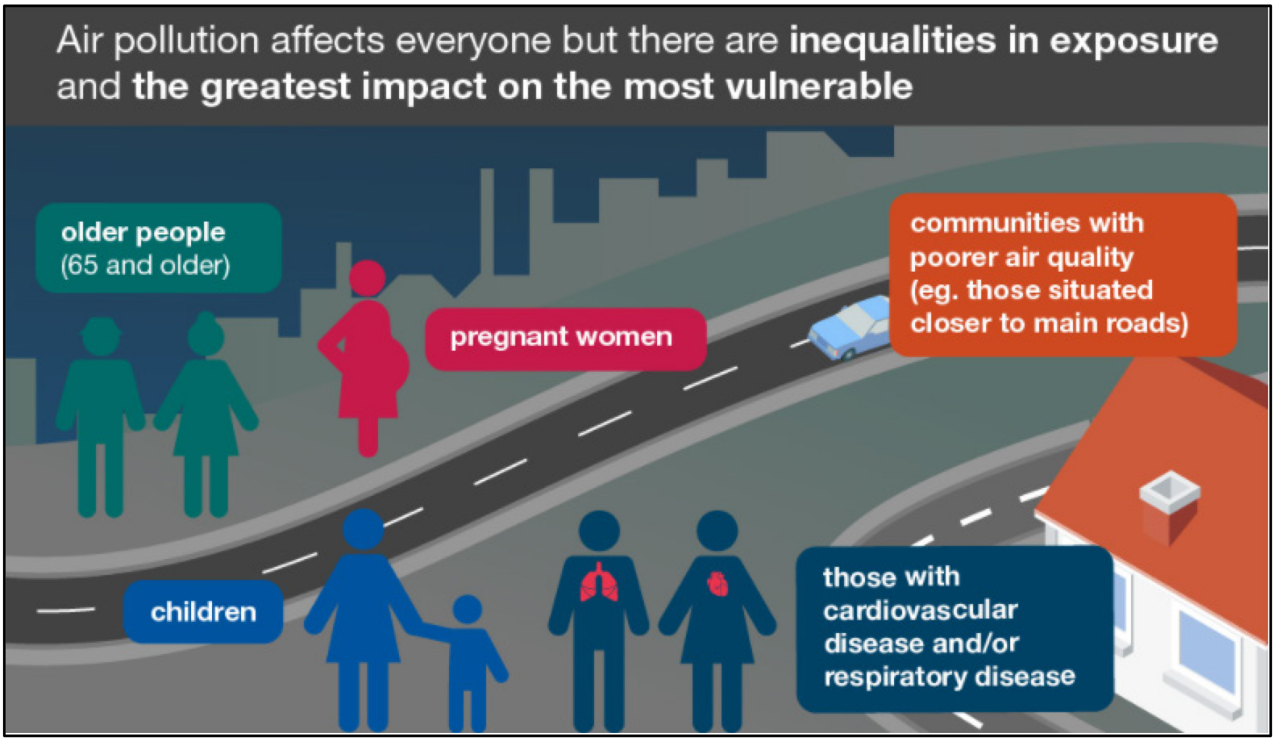
Introduction

There is growing awareness of the need to improve the quality and provision of information of the health impacts of air pollution and the actions that can be taken to better engage the public, particularly the vulnerable groups most impacted by poor air quality: older people, pregnant women, children, those with cardiovascular disease or respiratory disease, and communities with poorer air quality (Figure 1).

Figure 1. Groups most vulnerable to the impacts of air pollution (1)



Information about day-to-day levels of air pollution can be found on the Department for Environment, Food and Rural Affairs' (Defra) UK-Air website, which features a Daily Air Quality Index (DAQI). The index is numbered 1 to 10 and divided into 4 pollution bands: low ('1') to very high ('10'). Each band has recommended actions and health advice for both the general population and at-risk individuals. Alongside the DAQI, several other websites and messaging services are used to disseminate and communicate information and alerts. They include the Clean Air Hub, which provides information for the public and health and care professionals about the health effects of air pollution and actions they can take.

In 2021, an inquest into the death of Ella Adoo Kissi-Debrah following an asthma attack found that air pollution "made a material contribution" to her death and a 'Prevention of Future Deaths report' (2) was published in which the coroner stated:

"There is a low public awareness of the sources of information (such as [the] UK-Air website) about national and local pollution levels. Greater awareness would help individuals reduce their personal exposure to air pollution. It was clear from the evidence at the inquest that publicising this information is an issue that needs to be addressed by national as well as local government."

Improving public awareness and reducing exposure to air pollution

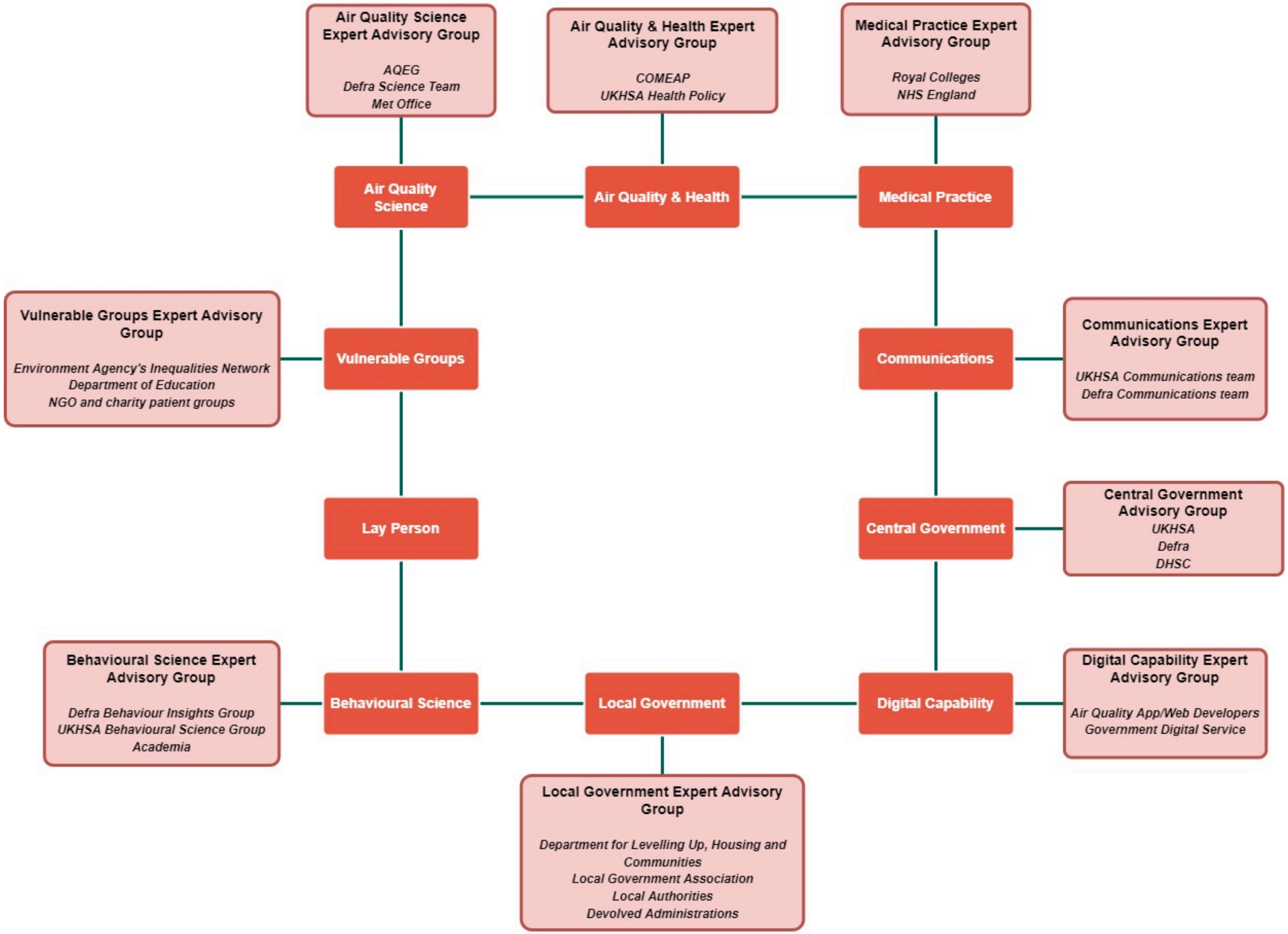
In June 2021 the responsible Central Government Departments (CGD) – Defra, the Department for Transport (DfT), and Department of Health and Social Care (DHSC) – provided their response to the 'Prevention of Future Deaths report' (3). One of the commitments made in the response was for Defra, the UK Health Security Agency (UKHSA) (formerly Public Health England) and DHSC to establish an expert group to steer an overhaul and update of the UK-Air website, including the DAQI and its associated advice, in the light of accumulated new evidence and lived experience.

The proposed review will bring together various strands of work related to air quality alerts, advice, and guidance, to provide clear, actionable recommendations on the changes that need to be made to the present system to better meet the needs of individuals, healthcare professionals, government bodies and other key users. The review will examine the Air Quality Information System (AQIS) in its entirety, including how information is delivered and messaging content. The steering group will exist for 2 years, and recommendations can be made throughout this time.

The Air Quality Information System (AQIS) Steering Group

To ensure a holistic review of the AQIS, including the DAQI, is undertaken, a multi-disciplinary steering group has been established. Figure 2 and Table 1 show its structure and membership, which includes representation from the Central Government Departments and agencies with the greatest responsibility for and most interest in alerting the public about poor air quality. Membership includes independent experts in air quality science; the health impacts of air pollution; the treatment of relevant conditions; health inequalities; behavioural science; and communications, including digital capabilities. It will also include representation from members of the public and those vulnerable to the effects of poor air quality. Members provide links to existing Advisory Groups and wider expertise in each specific discipline.

Figure 2. The structure of the AQIS steering group



Each independent expert will be responsible for building and maintaining a network of wider stakeholders from within their field of expertise. This will act as a specialised advisory group, and the steering group member will feed in the views of the advisory group to the wider steering group.

Table 1. Members of the AQIS steering group

Air quality science	Ally Lewis (Chair of the Air Quality Expert Group (AQEG))	**Behavioural science**	Kirsty Smallbone (Dean, School of Applied Sciences, University of Brighton)
Air quality and health	Anna Hansell (Chair of the Committee of Medical Effects of Air Pollutants (COMEAP))	**Communications**	Defra communications team
Medical practice	Jo Feary (Consultant, Royal Brompton and Harefield Hospitals)	**Local government**	Matthew Clarke (Program Manager – Air Quality, Hertfordshire County Council)
Vulnerable groups	Rob Day (Policy and Public Affairs Officer, Asthma UK and the British Lung Foundation)	**Digital capability**	Andrew Grieve (Senior Air Quality Analyst, Imperial College London)
Lay person	Gillian Mawdsley	**Central government**	Karen Exley (UKHSA), Sarah Peters (DHSC), John Newington (Defra)

The group will be chaired by Bill Parish, Deputy Director, Air Quality and Industrial Emissions (Defra). Professor Stephen Holgate, Medical Research Council Clinical Professor of Immunopharmacology (University of Southampton), and UKRI Clean Air Champion, will provide project assurance as advisor to the chair.

The future aims of the AQIS review

The group will consider the nature, uptake, and impact of an air quality information system that seeks to both reduce people's exposure to air pollution and encourage personal action to reduce emissions. The steering group will decide what the review should prioritise, but foreseeable areas of interest include reviewing the latest evidence and understanding of:

- the range of and levels at which air pollutants impact human health (and their implications for threshold levels used in the DAQI)
- the associated actions that the general public and at-risk groups are advised to take to protect their health, including differentiated advice for different groups

- actions that the general public can take to reduce air pollution, including specific actions that could be taken to lessen the severity of particular types of short-term episodes of poor air quality
- the system(s) by which advice could be most effectively communicated to the public (and at-risk groups)
- how to provide impactful messages and effective and actionable advice to different groups, considering people's responses to messages and the risk of unintended consequences
- the potential impact that improvements to the air quality information system could have and determine what measures of success should be for future evaluation

Next steps

The steering group will meet every 2 months for a period of 2 years. Outcomes from the review will be published throughout the two-year period (on the UK-AIR website). Clear, actionable recommendations will be made regarding any changes that should be made to the present system or gaps in current understanding that need to be addressed to improve air quality information provision in the UK. The UKHSA, Defra and DHSC are currently working with members of the steering group to develop a communications strategy to ensure all interested parties are kept up to date with progress.

Acknowledgements

The authors would like to thank Eleanor Sykes for her invaluable contribution to this work.

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Developing an air pollution exposure surveillance system in England

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Introduction

Air pollution has been highlighted as the largest environmental risk to public health in the UK. It shortens lives and contributes to chronic and non-communicable diseases. Public Health England's (PHE's) strategic plan for 2020 to 2025 specified a priority focus on clean air, and the development of enhanced data and surveillance capabilities amongst its top 10 priorities (1). The UK Health Security Agency (UKHSA) continues PHE's development of evidence-based methods to accelerate improvements to air quality and reduce risks to health for current and future generations. As part of this work, UKHSA conducts environmental public health tracking and surveillance of environmental hazards and exposures including air pollution.

A surveillance system for air pollution

The objectives and features of an epidemiological surveillance system for air pollution in England have been defined as part of UKHSA's Environmental Public Health Tracking (EPHT) programme (2). The development of this new surveillance system for air pollution will directly address aspects of relevant recommendations made by the Chief Medical Officer in the 2017 Report on 'Health impacts of all pollution' (3).

The EPHT programme was set up to support a framework within which to develop surveillance infrastructure and information systems. Stakeholders identified air pollution as a key priority for environmental heath surveillance and intelligence. We established an Air Pollution Exposure Surveillance (APES) Working Group to develop this work, comprised of subject-matter experts drawn from a range of specialist domains within UKHSA and including external stakeholder input where required. The APES working group first convened in February 2018.

The objectives agreed at the outset by the group were:

- to develop a national surveillance system of population exposure to air pollution, (considering both ambient and indoor aspects) that can be used by stakeholders for evaluation of interventions that aim to reduce air pollution exposure at population level
- the system should have the potential that in future it will be possible to incorporate linkages to health behaviours and outcomes

The working group considered how to deliver an air pollution exposure surveillance system to England after reviewing the US, French, German and Dutch methodologies. It reached a consensus to proceed with a human vulnerability approach, focusing on ambient outdoor air pollution first.

Current work

The aims of the project since 2019 were:

- to scope and develop pilots to demonstrate feasibility of air pollution exposure surveillance for stakeholders in England
- to agree potential new indicators to represent human vulnerabilities to air pollution
- to help identify areas with populations who are in sensitive and vulnerable population groups (as defined by age or socio-economic status (SES))
- to identify local authority (LA) actions (interventions) that aim to address air pollution problems, particularly in towns and cities with Air Quality Management Areas (AQMAs)
- to quantify indicator changes that relate to local actions and are relevant to local authorities

The project first focused on scoping initial pilots to develop an air pollution exposure indicator (see Box 1). The first stage of developing the exposure indicator was to assess sources of hazard data. Data sets on ambient outdoor particulate matter ($PM_{2.5}$) and nitrogen dioxide (NO_2) were compiled and methods to best estimate air pollution exposure determined. Population databases were used to develop vulnerability indicators (considering age, socio-economic status, locations of vulnerable subgroups, health conditions and so on). Georeferenced exposure and vulnerability data sets can either be combined to identify vulnerable groups or linked with health data to identify the health impacts associated with air pollution.

The second stage of the work has been to identify interventions that local authorities are introducing (or considering) to improve poor air quality and reflect how the new indicator can capture how changes affect vulnerable populations. The data and methodology required will be evaluated in an options appraisal.

Box 1: Steps in the development of a pilot vulnerability indicator

We compiled data sets to use in building the pilot indicators. We developed a pilot methodology of combining population, locational and air pollution data to develop a vulnerability indicator for all local authorities in England

We liaised with stakeholders as to what methodology to use, building local data sets and exploring what the outputs could look like

We identified pilot areas to build and test the indicators. We consulted with local authorities and other users to gain feedback on the usefulness and design of the indicator and how it can support local decision making

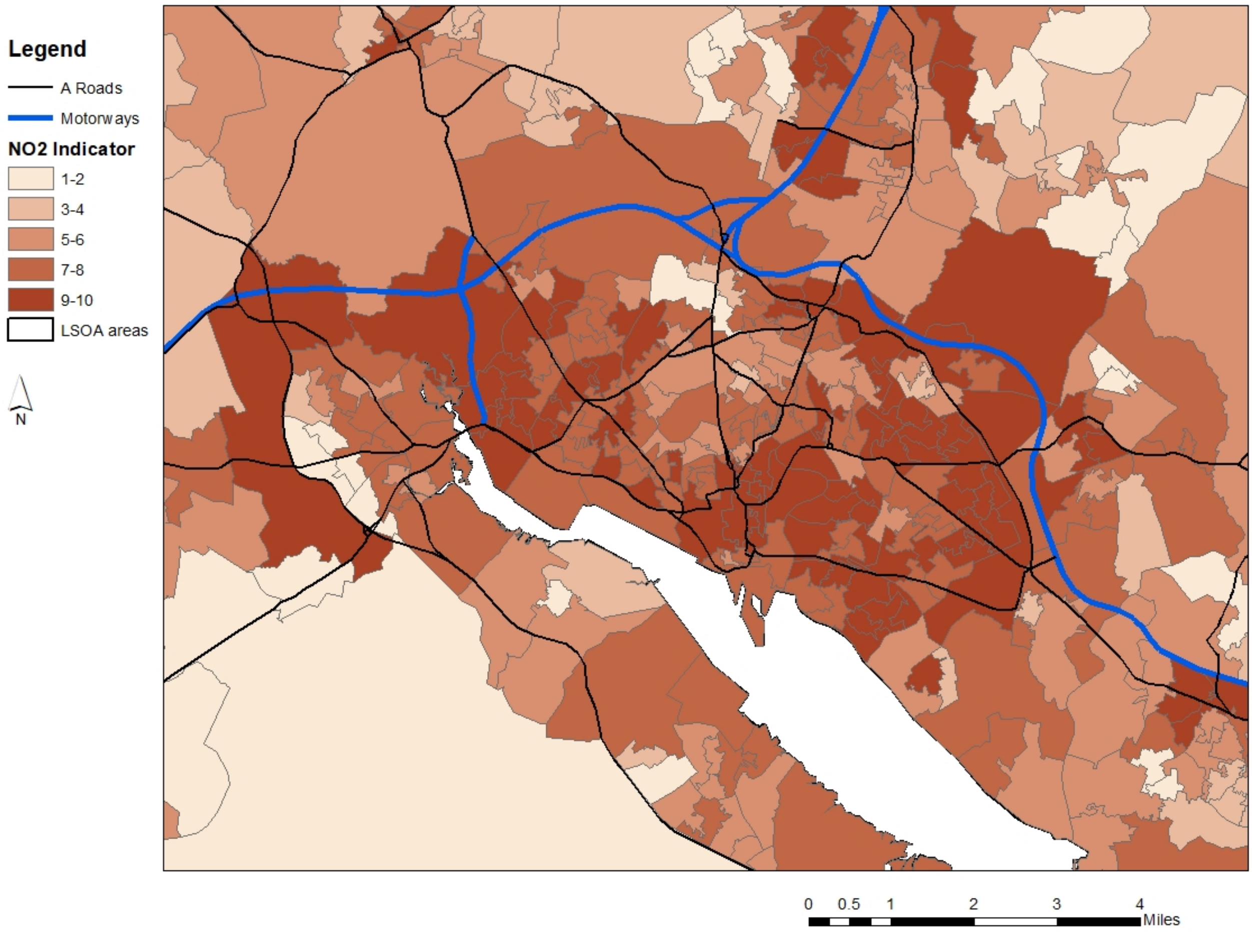
We explored options for hosting the indicator to make it publicly available online

We reviewed and categorised interventions to reduce poor air quality and gathered examples of best practice

Results

Maps were produced in ArcGIS for the vulnerability indicator for both NO_2 and $PM_{2.5}$ for every local authority in England. These show the vulnerability score at Lower Super Output Areas (LSOA) from 1 (low vulnerability) to 10 (high vulnerability). Figure 1 is an example output for Southampton City, for NO_2, based on 2018 population and air pollution data. Higher vulnerability can be seen in residential areas to the north of the city centre and along the M27 motorway corridor.

Figure 1. Example output of the UKHSA Air Pollution Exposure Surveillance – human vulnerabilities to air pollution exposure vulnerability indicator



Maps for upper and lower tier local authorities were produced and a series of interviews with 9 pilot authorities captured feedback on the local interpretation of the maps and how they could support local policy decision making. From a qualitative analysis, themes were drawn out until we reached saturation. The feedback suggested that local authorities welcomed these maps as they showed a different perspective and public health focus compared to traditional air pollution maps. Most local authorities preferred the double pollution weighted maps, which increased emphasis on concentrations as they related to areas with poor air quality. These maps are therefore being published on online platforms.

Two suitable hosting options were identified. The first output of the surveillance is being hosted in an Office for Health Improvement and Disparities (OHID) and UKHSA Air Quality Health Toolkit and in the online SHAPE Place Atlas (4).

Lessons learned and next steps

The indicator can be used to support local authorities in Joint Strategic Needs Assessments (JSNAs) and Air Quality Action Plans (AQAPs). The maps help to identify where a population-focused approach should address local vulnerability to poor air quality. Feedback from local authorities suggested weighting the pollution inputs so they had more of an effect on the indicator. We took this on board, so the maps better reflect pollution patterns. The maps can be used to address health inequalities and targeting actions to protect more vulnerable populations.

One limitation of these maps is they are built on nationally available data, so local data at a finer spatial resolution is not used. As a result, some local air quality hotspots are not reflected in the indicator.

Next steps include integrating the effect of interventions to reduce air quality and reflecting how this affects vulnerability. Health outcome data can also be added to highlight priority areas to address health inequalities.

The indicator and maps are available via an OHID and UKHSA Air Quality Health Toolkit currently under consultation. The maps are also available via the SHAPE Place Atlas (4). Access is free via registration.

For more information contact: epht@phe.gov.uk

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Feature article: Current understanding of the influence of the COVID-19 outbreak on the health effects of air pollution

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Key messages

There is some evidence that long-term exposure to air pollution increases susceptibility to more severe health outcomes from coronavirus (COVID-19), although more recent estimates of the increase in risk are lower than in many early studies. This link may result from the established link between air pollution and lung and heart disease, which are known to be risk factors for more severe COVID-19.

There are a small number of good quality studies in people infected with COVID-19 showing that long-term exposure to air pollution prior to the pandemic increased their risk of hospitalisation. Inconsistent results were found for studies investigating long-term exposure to air pollution and the number of COVID-19 cases and deaths.

There is some evidence that exposure to air pollution may increase the chance of infection by the virus. This is based on a biologically plausible mechanism suggested by animal studies that showed that air pollutants increase the amount of a specific proteins on the surface of the lung known to allow the virus to attach and enter the cells.

The most recent evidence suggests that particulate air pollution does not have an important role in transporting the virus in the environment. This is contrary to findings reported from some early studies.

The evidence for a link between short-term exposure to air pollution and COVID-19 incidence or severity continues to remain unclear and is difficult to evaluate based on the current evidence.

Lockdown measures used to control the spread of the virus resulted in reduced concentrations of some primary pollutants (NO_2 and to a lesser extent $PM_{2.5}$) most notably in urban environments. Changes in people's exposure is more uncertain, with exposure to traffic related pollution likely to have decreased, whereas increased time spent at home may have increased exposure to indoor air pollutants.

Introduction

Coronavirus disease (COVID-19) is an infectious disease caused by the SARS-CoV-2 virus, a pathogen that primarily targets the human respiratory system (1). There has been extensive research into the pathogenesis of COVID-19 (2) which suggests that the disease results from an excessive inflammatory response. Individuals over 60 years of age or with underlying health conditions, including cardiovascular and chronic respiratory diseases, diabetes, and cancer (due to weakened immune system) are at the highest risk of developing severe clinical symptoms and death.

Air pollution, in particular particulate matter ($PM_{2.5}$), nitrogen dioxide (NO_2), and ozone (O_3), has well-established adverse effects on respiratory and cardiovascular health (3). It is evident that patients suffering respiratory and cardiovascular disease have an increased risk of mortality from COVID-19 compared to healthy subjects (3). Also, it is well established that exposure to outdoor and indoor air pollutants predisposes people to, and worsens their outcome from, other respiratory infections, including acute upper and lower respiratory infections, bronchitis, bronchiolitis, pneumonia, and influenza (3). Consequently, it has been hypothesised that air pollution may also contribute to COVID-19 transmission and severity.

As the pandemic has progressed, it has become evident that socioeconomic and demographic factors are strongly associated with COVID-19 mortality rates (4), and these are also often associated with higher long-term exposure to $PM_{2.5}$ and NO_2. In addition, lockdown measures to control the spread of COVID-19 have resulted in short-term reductions in air pollution levels, which benefit health (5, 6). Consequently, it is challenging to interpret the correlation between both short-term and long-term air pollution concentrations and COVID-19 cases and mortality, and other geographical factors that can also influence the spread and severity of the disease.

Since the start of the pandemic in early 2020, a large number of studies have been published linking air pollution and COVID-19. These vary in quality and content.

This report reviews the evidence and what has been learned on the interaction between COVID-19 and air pollution. Specifically, the influence of air pollution on the susceptibility to and severity of COVID-19, how knowledge has changed since the start of the pandemic, and gaps in the evidence that need to be addressed. The review focuses on the epidemiological and toxicological evidence that has accumulated since the start of the pandemic.

The main sources of evidence referred to in this report are reviews from authoritative sources and selected key papers referred to in these reviews (see Approach section below). Additionally, some more recent relevant studies have been referenced, identified from daily searches of the literature undertaken by the United Kingdom Health Security Agency (UKHSA). Any additional studies were selected based on whether they inform or address gaps in the evidence identified by the authoritative reviews.

Approach

The main sources of evidence referred to in this report are reviews from authoritative sources, namely Brunekreef and others (7), Walton and others (8), and the Air Quality Expert Group (9) and selected key papers referred to in these reviews. Additionally, some more recent relevant studies have been referenced, identified from daily searches of the literature undertaken by the United Kingdom Health Security Agency (UKHSA). More recent relevant studies on the link between exposure to air pollution and COVID-19 have been identified by updating the search from the review undertaken by Walton and others (8) up to October 2021. Additional studies were included in the review based on whether they informed or addressed gaps in the evidence identified by the authoritative reviews.

Evidence on air pollution and COVID-19

Effects of short-term exposures on COVID-19 transmissibility and severity

Introduction

Short-term exposure to air pollution can interact with the SARS-CoV-2 virus through 2 potential pathways. Firstly, exposure to air pollutants in the short-term has the potential to lead to more severe consequences for people already infected with the virus. Secondly, short-term exposure may lead to changes that increase the likelihood of catching COVID-19.

Epidemiology

As reviewed by Brunekreef and others and Walton and others (7, 8), most studies that have looked at the effects of short-term exposure to air pollution on COVID-19 cases and deaths were located in Europe, North and South America and Asia. These investigated associations between COVID-19 outcomes and a range of different pollutants, including PM_{10}, $PM_{2.5}$, NO_2, O_3, sulphur dioxide (SO_2) and carbon monoxide (CO). The studies, particularly those undertaken early in the pandemic, tend to be based on time-series analysis and their statistical power to determine an exposure-response association is limited by a very short time-period of study during the pandemic (usually one or 2 months). To increase statistical power, the majority of studies have investigated confirmed COVID-19 cases, with fewer studies looking at COVID-19 mortality or other health outcomes.

A number of confounders are commonly controlled for in time-series analyses, such as meteorological and seasonal variations. However, other factors are also important when determining exposure-response associations with COVID-19 endpoints, including the timing of the increase in the rate of infection (relative to changes in air pollution), reporting of actual infection rates, infection control measures, and population mobility and density. Most of the studies published since the beginning of the pandemic have not adjusted for these important confounders, with only a small number of studies having accounted for these factors in their analyses. Confirmed COVID-19 cases, used in the majority of analyses, are only a proxy for the true infection rate as most asymptomatic cases or cases with mild symptoms may remain unidentified. Also, notification procedures may mean that there is a time delay in ascertaining the infection status of a case when compared to the time of onset of symptoms, which may affect the analysis (10). In addition, measures implemented to prevent the spread of the virus may also act as a confounding factor as they can also influence outdoor air pollution concentrations. Consequently, air pollution concentrations and exposure during the pandemic would be dependent upon the extent of lockdown measures employed and the effect of these measures on socioeconomic activity and vehicle use.

As discussed by Brunekreef and others (7) and Walton and others (8), there is considerable variation in the findings of studies investigating the effect of short-term pollution on COVID-19, which is likely to be explained by short time-periods, lack of adjustment for confounders and changes in lockdown measures. Whilst some studies reported a significant positive (adverse) association for specific pollutants, there are studies that reported no association or statistically significant negative associations (implying air pollution is having a protective effect).

The reviews by Brunekreef and others (7) and Walton and others (8) did not perform meta-analyses, however, another review (11) covering a similar period of time did so. It investigated the association between long-term and short-term exposure to air pollution and respiratory infections, including SARS-CoV-2. Publications up to October 2020 were reviewed, meaning that only SARS-CoV-2 studies from winter 2019 and spring 2020 were included. The study performed a meta-analysis of 30 short-term studies and showed a statistically significant positive associations between NO_2 and SARS-CoV-2 cases (RR 1·34 95% CI:1·03;1·74 for a $10 \mu g/m^3$ increase in NO_2). It was noted when comparing risk of bias ratings that the short-term studies scored poorly for the exposure assessment. Another study (12) performed a systematic review of 35 observational studies that were categorised based on long-term or short-term exposure, COVID-19 incidence or mortality, and by individual pollutant. The authors identified 15 short-term (time-series) studies, with most studies being considered as having a low risk of bias, although, the quality assessment used to determine the risk of bias was unclear. Meta-analyses for different pollutant-outcome pairs showed a positive (adverse) association between a $1 \mu g/m^3$ increase in NO_2 (effect size = 1.014, 95% CI:1.011;1.016), $PM_{2.5}$ (effect size = 1.003, 95% CI:1.002;1.004), PM_{10} (effect size = 1.005, 95% CI:1.003;1.008), SO_2 (effect size = 1.015, 95% CI:1.007;1.023) and COVID-19 incidence. An analysis (13) investigated the complexity in the relationship between factors influencing the spread and control of the virus and assessed the effect of air pollution, alongside a number of confounders, on COVID-19 outcomes in 615 cities from January to June 2020. It reported a strong positive association between air pollutants and COVID-19 cases. Increasing levels of $PM_{2.5}$, O_3, and NO_2 increased the propagation rate of COVID-19 by 0.31% (CI: 0.291;0.327), 0.37% (CI: 0.355;0.391), and 0.13% (CI: 0.107; 0.148), respectively

Walton and others (8) concluded that the epidemiological evidence does not provide a clear link between short-term exposure to pollution and COVID-19. More recent studies conclude that positive associations exist, however, the results of these studies should be interpreted with caveats as these associations may be the result of confounding. As described above, these types of study are inherently difficult to undertake well, due to the need to perform them over a short time period with rapidly changing infection rates and infection control measures.

Mechanistic studies

As discussed by Walton and others (8), short-term exposure to air pollution has been associated with day-to-day elevations in inflammatory markers including the cytokines IL-6, Il-1beta and TNF-alpha (14, 15). Similarly, in severely ill patients with COVID-19 disease, the tissue damage in the lung caused by the SARS-CoV-2 virus leads to excessive secretions of pro-inflammatory cytokines (particularly IL-6) and the recruitment of other pro-inflammatory cells such as neutrophils and monocytes (16). These cells release proteases (protein digesting enzymes) and reactive oxygen species to destroy pathogenic proteins. However, these molecules are not selective and so excessive quantities can result in further cell damage and an amplification of cytokine secretion and leucocyte recruitment and lead to a severe inflammatory response, a so-called ‘cytokine storm’ (17). Hence, it has been suggested that an additive effect occurs, with a heightened inflammatory state occurring in the inflamed lungs of COVID-19 patients that are also exposed to inflammatory air pollutants.

The cytokine storm and associated cell death in the lung is a determinant of the severe complications of COVID-19 disease, such as acute respiratory distress syndrome (ARDS), pneumonia (16). Walton and others (8) highlighted potential pathways by which exposure to air pollutants might exacerbate COVID-19 progression. There is limited evidence for the impact of short-term air pollution exposure on ARDS. However, a study (18) examined the effect of short-term PM (PM_{10}, $PM_{2.5}$, and PM_1) concentrations on daily emergency ambulance dispatches (EADs) for ARDS in China. The results indicated a significant positive association between EADs for ARDS and acute increases in PM.

Several cytokines are involved in the promotion of thrombosis, resulting in the production of microthrombi in the blood vessels. Microthrombi in cardiac blood vessels are associated with cardiac injury and failure in patients that develop severe COVID-19. Studies in healthy adults exposed to diesel exhaust have also reported platelet activation and increased thrombus formation (19 to 21).

In addition to an additive inflammatory effect, it has been postulated that short-term exposure to air pollution may facilitate infection with COVID-19 (22 to 24). The SARS-CoV-2 virus can target the respiratory tract because of the expression of angiotensin converting enzyme (ACE2) in the pulmonary epithelial cells (17). The protein ACE2 acts as the receptor for the attachment of the SARS-CoV-2 spike protein ‘S’ and, hence, increases the chance of infection and severity of disease. Once attached, the spike protein undergoes cleavage by trans-membrane protease serine 2 (TMPRSS2), allowing the virus to fuse with the cell membrane and enter the cell in order to replicate.

Walton and others (8) identified several model studies demonstrating that air pollution, in particular PM, can alter the expression of ACE2 and TMPRSS2. In vitro studies (25, 26) using human pulmonary cells have shown that $PM_{2.5}$ causes over expression of angiotensin converting enzyme-2 (ACE2). Additional animal studies (27 to 30) to those presented by Walton and others have shown $PM_{2.5}$ to alter ACE2 expression, although the evidence is conflicting with results showing both an increased and decreased expression. It has been hypothesised (31) that exposure to $PM_{2.5}$ induces an increase in transcription factors (TFs) that in turn promote the increased expression of ACE2. This activation of TFs can occur either directly (for example, by $PM_{2.5}$ induced activation of the aryl hydrocarbon receptor, AhR), or indirectly (for example, via the signal transducer and activator of transcription 3, STAT3, by increasing oxidative stress and inflammatory factors particularly interleukins). As discussed by Walton and others (8), a study (26) investigated the direct impact of PM exposure on infectivity. It used mice that had been bred to express human ACE2, exposed them intranasally to urban PM (NIST 1648) and after 3 days to intranasal SARS-CoV-2. The results were consistent with previous cell culture studies (26) and showed that PM-exposed mice expressed more ACE2 and TMPRSS2 than control mice and had higher viral loads 1 and 3 days post infection. In addition, PM-exposed mice exhibited higher expressed levels of COVID-19 associated inflammatory cytokines. The authors concluded that PM exposure had exacerbated pulmonary lesions and viral loads and had the potential to worsen the severity of the disease post infection. A more recent in vitro study (32) investigated whether diesel and woodsmoke altered gene expression in human nasal epithelial cells infected with SARS-CoV-2. The authors reported that exposure had no effect on viral load, however, exposure to woodsmoke (red oak smoke), but not eucalyptus smoke or diesel particulates, dampens the expression of antiviral genes and host defence genes with the effects being greater in cells from females than those from males.

Hence, there is recent evidence to suggest that air pollution can alter the expression of ACE2 and TMPRSS2 and thereby increases the susceptibility to, and severity of, infection by facilitating viral entry and reducing the host's defences. Studies indicate that inflammatory factors are critical in determining ACE2 expression following PM exposure. However, as noted by Walton and others (8), due to methodological challenges in the experiments, the effect of air pollution on infectivity is often inferred rather than measured directly and pollutant doses were considerably higher than those usually seen in ambient human exposure.

Effects of long-term exposure to pollutants on COVID-19 severity and outcomes as well as transmissibility

Introduction

It has been hypothesised that long-term exposure to air pollution can increase the number and severity of COVID-19 cases in 2 ways. Firstly, long-term exposure to air pollutants is known to be associated with an increase in the incidence of cardiovascular and respiratory diseases (3). The effect of long-term exposure to air pollution on heart and lung disease suggests that pollution could make individuals more likely to develop severe COVID-19 symptoms. In addition, if the cases in a population are generally more severe, this can result in a larger number of reported confirmed cases. Secondly, long-term exposure to air pollution may cause changes to the immune system increasing individuals' propensity for being infected by the virus and, consequently, leading to more cases within a population.

Epidemiology

As reviewed by Brunekreef and others (7) and Walton and others (8), several ecological studies have been undertaken with the aim of investigating whether long-term exposure to air pollution is potentially associated with an increased susceptibility to adverse COVID-19 outcomes, such as case number, hospitalisations, or deaths. These studies vary in their sophistication, with some showing simple correlations between regional long-term air pollution and COVID-19 mortality and others investigating the link between air pollution levels in an area (county, municipality) and COVID-19 mortality or case-fatality whilst adjusting for some confounders. The main limitation with most of these studies is that they are based on data for population groups and lack detailed information at an individual level. Furthermore, geographical areas not only have different air pollution levels but also differ by many other factors, for example, socio-economic, demographic, and genetic. This can lead to the so-called ecological fallacy whereby relationships tend to be larger when assessed at the group level than when assessed at the individual level. In addition, a number of initial studies were published before being peer-reviewed and had methodological flaws, such as, lack of adjustment for social contacts and mobility, which are important determinants for the spread of the virus. The importance of confounding factors is discussed by Brunekreef and others (7) and Walton and others (8) and is highlighted by an early study in the US which indicated that a 1μg/m^3 increase in long-term average county-level $PM_{2.5}$ concentrations was associated with a 15% increase in county level COVID-19 deaths (33). This estimate was reduced to 8% when the dynamics of the disease was accounted for based on the time of virus introduction in each county. Another study (34), using US county level data and a more thorough control for confounding and spatial autocorrelation, found only a marginal association between $PM_{2.5}$ concentrations and COVID-19 mortality, although an association with long-term exposure to NO_2 was reported.

An ONS study (35) investigated the relationship between COVID-19 mortality in England between March and June 2020 and long-term exposure to air pollution, using a statistical approach to address issues of collinearity between confounding variables and the spatial variation in rates of infection. The approach enabled an examination of how the correlation between COVID-19 death rates and air pollution changed over the course of the study period. The report concluded that there may be a correlation between $PM_{2.5}$ and NO_2 concentrations and COVID-19 mortality rates but the scale of the impact may be smaller than reported in papers early in the pandemic. Furthermore, this correlation reduced significantly after controlling for ethnicity as a confounding variable. This suggests that either $PM_{2.5}$ and NO_2 exposure is contributing to the poor outcomes of minority ethnic groups or that the correlation is due to the strong relationship between populations of minority ethnic groups and areas where the pollutants are high.

Over the course of the pandemic, the number of ecological studies within the evidence base with better adjustments for confounders has increased. As reported by Walton and others (8), in appropriately conducted and analysed studies, there is some evidence to support the hypothesis that long-term exposure to pollutants (particularly, PM and NO_2) are associated with increased COVID-19 infection severity. More recent studies (36 to 40), published after the Walton and others' review (8) and adjusting for a number of potential confounders, have looked mainly at associations with exposure to PM. From these, there is additional evidence (36 to 39) to support an association with long-term exposure to PM and COVID-19 mortality. Aliosi and others (36) analysed COVID-19 mortality data for 107 Italian territorial areas and assessed the relationship between $PM_{2.5}$ concentrations and COVID-19 mortality rate during 2020. They accounted for 28 confounders, including demographic, social, economic, educational, behavioural, health, mobility, climatic, and geolocation factors. The results showed that an increase in 1μg/m^3 in the exposure is associated with a 9% (95% CI: 6.5 – 11.6%) in the average mortality rate, conditional on all 28 confounders. Prinz and others (38) investigated the correlation between fine particulate air pollution and COVID-19 cases and fatalities by German county level data, and accounting for several socioeconomic and demographic confounders and distance to COVID-19 hotspots. They reported a positive correlation between COVID-19 deaths and a 1μg/m^3 increase in long-term $PM_{2.5}$ and PM_{10} (6.18, SD = 1.44 and 2.11, SD = 0.71 additional COVID-19 deaths per 100,000 inhabitants, respectively). This study also found a correlation between cases and a 1μg/m^3 increase in long-term $PM_{2.5}$ and PM_{10} (199.46, SD = 29.66 and 52.38, SD = 12.99 additional COVID-19 cases per 100,000 inhabitants, respectively). Another study (39), considered different periods during the pandemic from May to December 2020. It analysed long-term exposure to $PM_{2.5}$ (1999 to 2016) and the COVID-19 mortality rate for 96 French departments and considered temperature, health services, health risk, and socio-spatial factors as covariates. The authors reported that a 1μg/m^3 increase in the annual average $PM_{2.5}$ concentration was associated with a statistically significant increase in the monthly COVID-19 mortality rate (effect coefficients of 1.244, 1.258, 1.264, 1.267, 1.271, 1.258, and 1.151 in May, June, July, August, September, October, and November, respectively). However, the association decreased with time as the disease spread across the country.

However, the evidence remains inconsistent, and some studies (37, 40) suggest that the association is less evident when accounting for confounders. Davies and others (37) quantified excess all-cause mortality at ages 40 years and over for Middle Layer Super Output Areas (MSOAs) in England in the first wave of the pandemic (March to May 2020) to identify community characteristics associated with these patterns. The study reported no association between population density or air pollution (NO_2 and $PM_{2.5}$) and excess mortality. Similarly, a study by Yue and others (40) looked at data for 3,108 US counties between January and May 2020 and assessed associations between COVID-19 mortality and a series of risk factors including long-term exposure to $PM_{2.5}$. They concluded that population density and percentage of non-Hispanic Black individuals were the 2 most important factors responsible for the COVID-19 mortality rate and that $PM_{2.5}$ concentration had a relatively small impact.

There is less, but some, evidence to supporting an association with higher incidence of COVID-19. A recent study (12) performed a systematic review of 35 observational studies that were categorised based on long-term or short-term exposure, COVID-19 incidence or mortality, and by individual pollutant. The authors identified 19 long-term studies, with most studies being considered as having a low risk of bias, although the quality assessment used to determine the risk of bias was unclear. Meta-analyses were also undertaken for different pollutant-outcome pairs. Based on the number of estimates for each pollutant of between 4 and 12, the analyses showed a positive (adverse) association between long-term exposure to NO_2, $PM_{2.5}$, SO_2 and COVID-19 incidence and between NO_2 and $PM_{2.5}$ and COVID-19 mortality.

Another systematic review conducted in October 2020 (11) investigated the association between long-term and short-term exposure to air pollution and respiratory infections including SARS-CoV-2. The study performed a meta-analysis of 22 studies of long-term exposure (including 2 using individual data). An assessment of the risk of bias noted that long-term SARS-CoV-2 studies were better evaluated than short-term studies. A meta-analysis of the studies of long-term exposure showed a small but statistically significant positive (adverse) association for 10µg/m^3 increases in $PM_{2.5}$ and NO_2 and mortality from SARS-CoV-2 (RR 1·65; 95%CI: 1·09;2·49 and RR 1·19; 95%CI: 1·08;1·30 respectively). Similarly, positive associations were seen for incidence, however, the results were only statistically significant for NO_2 (RR 1·24, 95% CI: 1·15 to 1·32).

Ecological studies provide some evidence to support the hypothesis that long-term exposure to air pollution results in more severe outcomes of COVID-19 cases. This effect may be a possible explanation for increases in case numbers: if cases are generally more severe and, consequently, more likely to be reported. The proposed role of air pollution in increasing the propensity for infection and, therefore, being associated with higher transmissibility is unclear from the epidemiological evidence.

To increase the certainty in the evidence base, there is a need for studies using individual-level data which can enable a better control for confounding. However, this may be balanced by a loss of statistical power due to the smaller number of cases analysed.

A small number of studies based on individual data were reviewed by Walton and others (8), and some more recent studies have also controlled for individual confounders (41 to 43). These have indicated that more severe COVID-19 outcomes, such as higher hospitalisation rates, occur in people exposed to air pollution prior to the pandemic. For example, 2 cohort studies (42, 44) in the US, based on people diagnosed with COVID-19, found that long-term exposure to $PM_{2.5}$ was associated with an increased risk of hospitalisation (10% for each 1.9µg/m^3 increase in annual (2018) average $PM_{2.5}$ and 18% for each 1µg/m^3 increment in 10-year average $PM_{2.5}$, respectively). A further study (41), using NO_x as an indicator for traffic related air pollution, found statistically significant positive association with non-freeway NO_x and COVID-19 related outcomes (intensive respiratory support, Intensive Care Unit admissions, deaths, but not COVID-related hospitalisation). However, no association was found between non-freeway NO_x or total NO_x and COVID-19 related outcomes. Studies of COVID-19 mortality among cases provide more inconsistent results. One such study (45) using the community-based UK Biobank cohort found that 2010 mean concentrations of air pollutants (NO_x, PM_{10}, and $PM_{2.5}$ at residential address) were not associated with COVID-19 mortality in 2020. In contrast, another study in Mexico City (46) found an association (a 1µg/m^3 increase in $PM_{2.5}$ resulting in a 7.4% increase in COVID-19 mortality), but it was not clear on how many cases of mortality it was based. More recently a study (43) investigated individual data at the census tract level in Colorado, with 4 different models for $PM_{2.5}$ exposure. The results were dependent on the exposure model used. A 1µg/m^3 increase in long-term $PM_{2.5}$ concentrations estimated by the US EPA was associated with a 26% increase (RR: 1.26, 95% CI: 1.06; 1.48) in the risk of hospitalisations and a 34% increase (RR: 1.34, 95% CI: 1.02; 1.77) in mortality after controlling for 20 covariates. Results using other exposure estimates were not statistically significant.

A recent cohort study in Spain (47) examined the link between long-term air pollution exposure and COVID-19 infection by measuring antibody response. Sensitive antibody test data, collected prior to vaccination, was used to detect the current and past infection of participants and, thus, reduce possible bias inherent in previous studies reliant on test surveillance data or health records. The study also accounted for several confounding variables (including lifestyle factors, changes in lifestyle due to the pandemic, medical history, changes in residential address, deprivation, and population density), covered a relatively small geographical area, and used well-established air pollution models. The authors reported that air pollution concentrations estimated for 2018 to 19 were not significantly associated with SARS-CoV-2 infections, with risk ratios (RRs) of 1.07 (95% confidence interval, CI: 0.97, 1.18) for NO_2 and 1.04 (95% CI: 0.94, 1.14) for $PM_{2.5}$ per interquartile range (NO_2 IQR: 11.62µg/m^3 and $PM_{2.5}$ IQR: 1.86µg/m^3). In contrast, significant associations were reported with COVID-19 disease based on hospitalisations and self-reported symptoms, with adjusted RRs per IQR of 1.14 (95% CI: 1.00, 1.29) for NO_2 and 1.17 (95% CI: 1.03, 1.32) for $PM_{2.5}$. However, the size of this association is lower than those reported in many earlier studies. In a commentary on the study (48) it is suggested that these findings of an association with more severe COVID-19 disease is consistent with plausible mechanisms whereby air pollution increases the incidence of diseases that are risk factors for COVID-19, and effects on the immune system leading to increased case severity. It was noted that there was no significant association with infection, which would be expected if air pollution increases expression of the ACE2 receptor and TMPRSS2, as suggested from animal studies (see previous sections). This may be explained by infection being affected by air pollution in the short-term, with long-term air pollution exposure acting as a poor proxy for the exposures that occurred during 2020.

The report by Walton and others (8) concluded that ecological studies suggest an association between long-term exposure to PM and NO_2 and mortality from COVID-19. More recent studies have mainly investigated associations with exposure to PM and continue to be inconsistent in study design and the extent of control for confounders. However, there remains more evidence to support the association between long-term exposure, particularly to PM, and COVID-19 mortality than for effects of short-term exposure. There is less, but some, evidence supporting a link with COVID-19 incidence. In a discussion of studies with individual data, Walton and others (8) determined that there was evidence that long-term exposure to $PM_{2.5}$ leads to more severe COVID-19 disease, specifically higher hospitalisation rates. This conclusion continues to be supported by subsequent studies with individual data.

Mechanistic studies

It has been shown that individuals especially susceptible to severe COVID-19 infection are those with existing pulmonary or cardiovascular conditions, diabetes or compromised immune function. As there is evidence that chronic exposure to air pollution has adverse effects on these conditions, it is plausible that long-term exposure to air pollution increases risk of severe COVID-19.

As discussed by Walton and others (8), there is experimental evidence to show that air pollution can impair the host's immune defence mechanisms, increasing susceptibility to respiratory infections. This occurs by direct cell damage and indirectly through oxidative stress and inflammation, both in the lungs and systemically. Prolonged oxidative stress and inflammation in the lungs can lead to the breakdown of alveolar walls (a feature of emphysema and chronic obstructive pulmonary disease), bronchial constriction (associated with asthma), and pulmonary fibrosis (8). As described above and discussed by Walton and others (8), severe features of COVID-19 disease are associated with excessive inflammation (the so-called 'cytokine storm'). It has been suggested that a heightened inflammatory state may occur in COVID-19 patients that have been exposed to air pollution long-term. In addition, the macrophages of patients with pre-existing COPD and asthma have impaired function, reducing their ability to phagocytose pathogens and, thereby, increasing susceptibility to respiratory infections (8).

Walton and others (8) also report evidence reviewed by Bevan and others (49) that chronic air pollution exposure can promote atherosclerosis (development of fatty plaques on blood vessel walls) and precipitate cardiovascular conditions known to be risk factors for COVID-19. Again, plaque formation may result from initial oxidative stress and inflammatory mediators occurring in the lungs, leading to systemic inflammation, dysfunction of the vascular endothelium, thrombosis promotion, and changes in blood pressure (15).

Similarly to short-term exposure to air pollution (see previous section), it is also plausible that long-term exposure can lead to increased susceptibility to COVID-19 infection. However, Walton and others (8) did not find any toxicological studies that directly investigated this effect. One study (50) investigated the expression of gene signatures associated with susceptibility to COVID-19 in lung tissue collected from mice following sub-chronic ozone exposure. They showed that a significant proportion of genes known to facilitate cell infection with SARS-CoV-2 were upregulated in the ozone exposed mice. Walton and others (8) interpreted these results as indicating that changes in the expression of these host susceptibility genes may continue to occur with ongoing, long-term exposure to pollutants.

In addition, impaired immune cell function has been proposed as an explanation for observed associations between long-term air pollution exposure and respiratory tract infections and may also occur with COVID-19. Walton and others (8) found limited evidence to support this, although, a reduced release of oxidative species and inflammatory cytokines has been reported in healthy individuals exposed chronically to smoke whilst cooking using biomass (51). Overall, Walton and others (8) concluded that further evidence is required to determine whether long-term exposures to air pollution impacts the host's immune system leading to more severe disease outcomes in the presence of COVID-19.

Studies on whether the virus can be transmitted via ambient particulate air pollution

The SARS-CoV-2 virus is recognised as spreading from an infected person's mouth or nose in small, aerosolised droplets following coughing, sneezing, or breathing. These particles range in size from larger respiratory droplets to smaller aerosols. Current evidence suggests that the virus spreads between people in close contact, typically within 1 metre, however, smaller aerosols can remain suspended in the air and travel further than 1 metre (52). This longer-range mode of transmission has led to various studies examining the possibility that particles in the air may act as carriers of virus-laden respiratory particles, enhancing the transmission of the virus in more polluted areas. An early study (53) supporting this hypothesis detected SARS-CoV-2 virus in PM_{10} collected in Northern Italy, an area severely affected by COVID-19 and characterised by high concentrations of PM. The report by Walton and others (8) provided an overview of studies investigating whether transmission of the virus was linked to particulate air pollution. One such study (54) investigated the presence of SARS-CoV-2 RNA on ambient particulate matter ($PM_{2.5}$ and PM_{10}) recovered in February and March 2020 from samplers sited in Padua, Italy. RNA extraction and detection showed no successful amplification of virus target genes in any of the tested samples and concluded that the virus RNA was not present or fell below the limit of detection. A similar study (55) investigated the possible presence of SARS-CoV-2 RNA on ambient particulate matter samples from sites in 10 cities in Turkey. It reported that viral genes were detected in 9.8% of samples, with the highest percentage of virus detection occurring on PM samples from hospital gardens. A further study (56) analysed indoor PM ($PM_{2.5}$) collected from 4 hospital wards of different dimensions occupied by different numbers of COVID-19 patients. SARS-CoV-2 virus RNA was detected in samples from 2 of the wards and suggested that the number of airborne particles with viral RNA in enclosed environments was dependent on the number of patients and the severity of their symptoms. However, although the above studies

(55, 56) detected RNA during the sampling they concluded that there was no direct link between PM and COVID-19 transmission. In all these studies, the presence of viral RNA on PM does not provide evidence of a viable virus that has the potential for infection if these particles were inhaled. Monitoring of SARS-CoV-2 RNA in outdoor air is unlikely to be a suitable early indicator of viral diffusion or pandemic reoccurrence (57).

Walton and others (8) concluded that, unlike studies early in the pandemic, more recent studies appear to support the conclusion that air pollutants do not have an important role in transporting the virus in the environment. This conclusion is supported by a more recent review (58) of the available literature, which found that there is a limited number of studies to support the spread of the virus via PM and was critical of the analytical procedures and methodologies that many of the studies employed. They concluded that more research is necessary for a better understanding of this potential phenomenon. Currently, there is a lack of scientific evidence that ambient air pollution plays a role in the direct transmission of the virus through the air.

Changes in air pollution levels and mixtures because of measures taken to reduce COVID-19 transmission

Changes in air pollution concentrations during the first lockdown in the UK were evaluated by the Air Quality Expert Group (AQEG) (9). Lockdown measures introduced to control the COVID-19 pandemic have resulted in some significant reductions in air pollutant emissions and concentrations, although with notable differences between pollutants, and rural and urban locations (9). These pollution changes correlated with changes in activity as a consequence of lockdown measures. Restricted mobility caused a reduction in transport activities, particularly road traffic, rail, and aviation, with vehicle traffic decreasing by approximately 70% in the UK. It is also expected that lockdown reduced activities and, consequently, emissions from construction, commercial heating, combustion, and industrial processing and power generation. Significant reductions in air pollution from lockdown measures were also seen across Europe in 2020, again with notable differences between pollutants, countries, and cities (7). AQEG (9) reported the most significant changes in air pollution in the urban environment. Mean reductions in urban NO_x averaged over the period of lockdown were 30% to 40%, with mean NO_2 concentrations reduced by 20% to 30% once meteorological effects had been considered. A consequence of reductions of primary NO emissions in urban areas is a concomitant increase in urban ozone (O_3) concentrations due to a decrease in the chemical loss of O_3 through the rection with NO. Meteorological conditions and the transport of particulates from wider regions during the first lockdown led to higher $PM_{2.5}$ concentrations than the average experienced from previous years. However, modelled data indicated that $PM_{2.5}$ concentrations were approximately 2 to 5µg/m^3 lower in Southern England than would have been expected compared to a business-as-usual scenario.

AQEG noted that there is limited information on the impact of lockdown on indoor air quality. Lockdown has resulted in more people working from home and generally spending more time indoors in their homes. This has potentially led to increased exposures to sources of indoor air pollution. However, whilst increases in exposure to indoor air pollutants is expected, this may be mitigated by a reduction in exposure related to commuting and a general reduction in outdoor air pollution. An exposure model accounting for both indoor and outdoor pollution predicted a net increase in $PM_{2.5}$ exposure for most individuals (apart from London Underground commuters) as a result of lockdown assuming that additional domestic cooking is performed each day. AQEG suggested that, as more time was spent at home, more activities will take place that are likely to affect indoor air quality, including smoking, cooking, cleaning, hobbies and craft activities and solid fuel burning. In addition, increases in outdoor ozone concentrations during lockdown would be expected to lead to greater concentrations of ozone indoors, which can then react with indoor sources of volatile organic compounds (VOCs) to produce potentially harmful by-products. Overall, people's exposure to pollutants in the air during the pandemic would have been affected by changes in outdoor emissions, behavioural changes resulting from lockdown measures and the effect of this altered behaviour on indoor pollution and exposure.

Evidence on diseases associated with air pollution during lockdown

Short-term exposure to elevated levels of air pollution has been shown to cause a range of health impacts, including effects on lung function, exacerbation of asthma, and increases in respiratory and cardiovascular hospital admissions (3). Consequently, there has been a number of studies investigating the link between these health effects and the observed decline in some air pollutants (NO_2 and PM) resulting from measures used to control the spread of COVID-19. These types of studies were not included in the literature reviews by Brunekreef and others (7) and Walton and others (8). For example, various studies have reported an association between the reduction in pollution levels and reduced hospital admissions for asthma (59, 60), stroke (61), COPD (59, 62), and signs for myocardial ischemia (63).

As discussed by the studies' authors, it is conceivable that some of the observed decreases in these disease outcomes may be linked to changes in air pollution. However, it is difficult to draw strong conclusions due to the influence of other confounding variables associated with lockdown measures. These include behavioural changes that may change the risk for a disease, such as social distancing and hygiene measures (reducing the exposure to other respiratory tract infections), and changes in levels of stress, physical activity, diet, and smoking. Factors such as avoidance of healthcare and the pressure on the healthcare system caused by the pandemic could result in under reporting of health outcomes. Two studies investigating hospital admission of stroke (64) and acute coronary syndrome (65) during the pandemic either did not find an association with short-term changes in air pollution concentrations or found a change in admissions even when accounting for air pollution. The authors suggest other factors, such as those described above, may have an important role in accounting for changes in admission numbers.

Further studies (66, 67) have used exposure-response functions, derived prior to the pandemic, to try to estimate the short-term health benefits associated with decreased pollution levels during lockdown. However, as discussed by Walton and others (8), it is difficult to estimate health benefits based on previously derived concentration-response functions as individuals' exposure to air pollution would be expected to change markedly during periods of lockdown, for example, due to more time spent indoors, less time spent commuting, and from less exposure to traffic related pollutants in general. The previously derived concentration-response functions are based on outdoor air pollution concentrations acting as a proxy for personal exposure to outdoor air pollutants, and this proxy relationship will have changed during lockdowns for the reasons explained above.

Recovery from COVID-19 and air pollution

In addition to the potential for air pollution to influence the transmission of and susceptibility to COVID-19, it is plausible that air pollution may have an effect on recovery from the infection, with recovery benefiting from cleaner air. However, to date there is limited evidence in the literature to support this effect. One study (68) compared daily COVID-19 recovered cases during a period of lockdown with daily air quality data in Wuhan, China. They observed a negative (adverse) association between COVID-19 recoveries and concentrations of air pollutants; however, this was a short-term study that did not consider potential confounders.

Vaccine effectiveness and air pollution

There is limited evidence of the influence of exposure to air pollution on the efficacy of the SARS-CoV-2 vaccine. A study (69) looked at daily exposures to air pollution and plasma neutralising antibody (Nab) titres of an inactivated SARS-CoV-2 vaccine in vaccinated healthcare workers. The authors reported that daily exposure doses of air pollutant were significantly and negatively associated with plasma Nab, suggesting that exposure to air pollution may inhibit Nab expression and reduce immunity. The authors concluded that this is a plausible effect and requires further investigation.

Evidence limitations and gaps

Brunekreef and others (7) and Walton and others (8) described limitations in the evidence base and recommendations for further work to better understand the link between air pollution and COVID-19. The gaps in the evidence highlighted in these reviews remain pertinent. Some of the key gaps are summarised below.

There are inherent limitations of time-series studies used to study the effect of air pollution on infectious disease epidemics over short periods of time. The short time frame makes it difficult to control for meteorological and seasonal effects and represent characteristics of the disease (such as incubation period, prolonged health effects, and time of death). Time series studies also need to try and account for factors that change over time, such as changes in public health policy (for example, COVID-19 testing, physical distancing, hand washing, wearing of facemasks), pressures on the healthcare system for testing and treatment, and clustering of cases. Hence, longer time-series analyses are required that are able to consider different stages during the progression of the pandemic to be able to draw more robust conclusions on the short-term exposure to air pollution and COVID-19.

It is also uncertain, based on current evidence, which pollutants have the strongest associations with adverse COVID-19 outcomes as most pollutants have common sources making it difficult to separate their independent effects. To identify the most harmful pollutants, more studies using multi-pollutant models that account for correlated exposures to different pollutants are required.

The majority of long-term studies in the literature employ an ecological design using aggregate data averaged over geographical areas. Such studies are generally regarded as hypothesis generating rather than providing concentration-response relationships. Therefore, additional, well-designed studies that use clinically characterised individuals, who are then followed over time, are required to investigate COVID-19 morbidity and mortality in relation to air pollution and other potential risk factors.

Definition of cases and deaths and testing capability and capacity have changed during the course of the pandemic and identification of cases is still challenging as asymptomatic individuals can pass on the virus. This has the potential to introduce bias when designing cohort studies if testing for COVID-19 was not done consistently across areas with different levels of air pollution. Therefore, carefully designed studies are required to overcome these potential problems and determine how air pollution is associated with infection and transmission of the virus (70).

Changes in the expression of the ACE2 enzyme in the lungs remains a plausible mechanism by which air pollutants may increase the infectivity of the SARS-CoV-2 virus. Further research is required to understand which pollutants alter ACE2 expression and the biochemical pathways involved.

There is limited information in the literature on how exposure to air pollution may affect patient care and recovery from COVID-19 or if it could alter the efficacy of immunity provided by vaccinations.

Conclusions

The link between air pollution and COVID-19 is challenging to study because measures implemented to control transmission of the virus also influence levels of air pollution (70). In addition, even with more extensive and accurate testing for the virus, the relationship between actual cases and reported cases will vary as the pandemic changes over time.

Although poor quality studies continue to be published, increasingly better-quality studies are being added to the evidence base, including those based on individual-level data and accounting for potential confounders. These individual-level studies suggest an association between long-term exposure to air pollution and hospital admissions for COVID-19, most likely due to the link between air pollution and respiratory and cardiovascular disease, which are known to be risk factors for more severe COVID-19 disease. Preliminary toxicological data supports the hypothesis that air pollution could have an effect of increasing the expression of receptors and proteins involved in viral entry into host cells. There is a theoretical possibility that particulate matter may facilitate transmission of the virus, however, recent studies do not appear to support this effect.

Overall, air pollution is known to cause diseases that are a risk for severe COVID-19 illness and, consequently, may increase the susceptibility of the population to infectious agents such as the SARS-CoV-2 virus. In general, populations with less exposure to ambient air pollution are at reduced risk of chronic disease and would be expected to be more resilient during a pandemic.

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Appendix: UKHSA Cleaner Air Programme publication list

Improving the evidence base

Osborne S, Uche O, Mitsakou C, Exley K, Dimitroulopoulou S. 'Air quality around schools: Part I – A comprehensive literature review across high-income countries'. Environmental Research 2021: volume 196, article number 110817

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Ferguson L, Taylor J, Zhou K., Shrubsole C, Symonds P, Davies M, Dimitroulopoulou S. 'Systemic inequalities in indoor air pollution exposure in London, UK'. Building and Cities 2021: volume 2, issue 1, pages 425–448

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Mitsakou C, Adamson JP, Doutsi A, Brunt H, Jones SJ, Gowers, AM, Exley KS. 'Assessing the exposure to air pollution during transport in urban areas – Evidence review'. Journal of Transport and Health 2021: volume 21, article number 101064

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Delgado-Saborit JM, Guercio V, Gowers AM, Shaddick G, Fox NC, Love S. 'A critical review of the epidemiological evidence of effects of air pollution on dementia, cognitive function and cognitive decline in adult population'. Science of the Total Environment 2021

Khan MS, Douglas P, Hansell AL, Simmonds NJ, Piel FB. 'Assessing the health risk of living near composting facilities on lung health and fungal and bacterial disease in cystic fibrosis: a UK registry study'. Submitted to Journal of Cystic Fibrosis

Bhui K, Newbury JB, Latham RM, Ucci M, Nasir ZA, Turner B, O'Leary C, Fisher HL, Marczylo E, Douglas P, Stansfeld S, Jackson SK, Tyrrel S, Rzhetsky A, Kinnersley R, Kumar P, Duchaine C, Coulon F. 'Air quality and mental health: evidence, challenges and future directions'. Wellbeing, Space and Society (pre-print)

Anees-Hill S, Douglas P, Pashley CH, Hansell AL, Marczylo EL. 'A systematic review of outdoor airborne fungal spore seasonality across Europe and the implications for health'. Science of the Total Environment 2021

Douglas P, Fecht D, Jarvis D. 'Characterising populations living close to intensive farming and composting facilities in England'. Frontiers of Environmental Science and Engineering 2021: volume 15, issue 3, page 40

Roca-Barcelo A, Douglas P, Fech D, Freni Sterrantino F, Williams B, Blangiardo M, Gulliver J, Hayes ET, Hansell AL. 'Risk of respiratory hospital admission associated with modelled concentrations of *Aspergillus fumigatus* from composting facilities in England'. Environmental Research 2020: volume 183

Increasing awareness and understanding

Dimitroulopoulou, S. 'Indoor Air Quality and Health'

Waterall J, Rhodes D, Exley K. 'Why air pollution is an important issue for all nurses'. British Journal of Nursing 2021: volume 30, issue 16, pages 982-983

Supporting and influencing stakeholders

World Health Organization (WHO). 2021. 'Screening questionnaire for selection of sampling sites for assessment of risks from combined exposure to multiple chemicals in indoor air'

World Health Organization (WHO). 'Educational tool for schools on chemical pollution of indoor air and its risk for children's health'

Greater London Authority (GLA). 2022. Borough Air Quality Guidance reports for Public Health Professionals (2022)

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