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Impacts of emissions policies on future UK mortality burdens associated with air pollution

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ABSTRACT

Air pollution is the greatest environmental risk to public health. Future air pollution concentrations are primarily determined by precursor emissions, which are driven by environmental policies relating to climate and air pollution. Detailed health impact assessments (HIA) are necessary to provide quantitative estimates of the impacts of future air pollution to support decision-makers developing environmental policy and targets. In this study we use high spatial resolution atmospheric chemistry modelling to simulate future air pollution concentrations across the UK for 2030, 2040 and 2050 based on current UK and European policy projections. We combine UK regional population-weighted concentrations with the latest epidemiological relationships to quantify mortality associated with changes in $PM_{2.5}$ and NO_2 air pollution. Our HIA suggests that by 2050, population-weighted exposure to $PM_{2.5}$ will reduce by 28% to 36%, and for NO_2 by 35% to 49%, depending on region. The HIA shows that for present day (2018), annual mortality attributable to the effects of long-term exposure to $PM_{2.5}$ and NO_2 is in the range 26,287 – 42,442, and that mortality burdens in future will be substantially reduced, being lower by 31%, 35%, and 37% in 2030, 2040 and 2050 respectively (relative to 2018) assuming no population changes. Including population projections (increases in all regions for 30+ years age group) slightly offsets these health benefits, resulting in reductions of 25%, 27%, and 26% in mortality burdens for 2030, 2040, 2050 respectively. Significant reductions in future mortality burdens are estimated and, importantly for public health, the majority of benefits are achieved early on in the future timeline simulated, though further efforts are likely needed to reduce impacts of air pollution to health.

1. Introduction & background

Exposure to poor air quality is the greatest global environmental risk to health, with ambient air pollution contributing to 4.2 million deaths annually worldwide (World Health Organization, 2021b). In the UK, long-term exposure to ambient air pollution is estimated to have an effect equivalent to 29,000 – 43,000 deaths annually (Mitsakou et al. 2022). The associations between long-term exposure to particulate matter and nitrogen dioxide (NO_2) and increased mortality from all causes, cardiovascular disease, respiratory disease and lung cancer are well established by several epidemiological studies (e.g. Chen and Hoek 2020; Huang et al. 2021). Fine particles ($PM_{2.5}$, particles with aerodynamic diameter < 2.5 µm) have a greater impact on health than larger particles as their smaller size means they are able to penetrate deeper into the respiratory system (World Health Organization, 2021c). Exposure to fine particulate pollution has also been associated with neuroinflammation and altered immune response, and there is also evidence that fine particles may make their way into the brain and liver (Calderón-Garcidueñas et al. 2004; Calderón-Garcidueñas et al. 2008; Oberdörster et al. 2004).

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Ambient air pollution levels are primarily driven by emissions (both direct emissions of pollutants and emissions of precursors that form secondary pollutants), with meteorology also influencing pollution concentrations via its impacts on pollutant transport and dispersal, chemical transformation, deposition and resuspension. Air pollutants often have common sources with greenhouse gases, for example combustion processes related to power generation, transport, and heating. Measures to reduce greenhouse gas emissions through switching to clean energy sources (for example renewable technologies such as wind and solar power, and electric vehicles), and reducing energy demand through improved efficiency, can therefore also have important benefits to health through improving air quality. A UK-focused review found that, in general, impacts from ambient air pollution on human health are expected to decrease in future due to net-zero and emissions control policies, but risks to health will still remain (Royal Society, 2021). Modelling studies have quantified the projected benefits to air quality and health of climate mitigation policies; for example, $PM_{2.5}$ concentrations in Great Britain are predicted to decrease by around 43% by 2050 (compared to 2011) for scenarios meeting a commitment of 80% reduction in CO_2 equivalent emissions by 2050 (Williams et al. 2018), while globally a rapid phase out of fossil fuels could avoid an excess mortality rate of $\sim$ 3.6 million annually from ambient air pollution (Lelieveld et al. 2019). Such evidence is used to strengthen the case for ambitious policy through demonstrating mutual benefits to health and climate (World Health Organization, 2021a).

Climate change itself also has the potential to impact air quality through its impact on local meteorology and the subsequent impacts of this on processes determining air pollution concentrations (Doherty et al. 2017; von Schneidemesser et al. 2015). Research has however generally shown that anticipated changes in anthropogenic emissions are likely to be the strongest driver of annual air pollution levels in the next few decades (Cholakian et al. 2019; Colette et al. 2013; Doherty et al. 2017; Geels et al. 2015; Hedegaard et al. 2013; Watson et al. 2016). Hence our focus in this study is on the impact of future emissions on health burdens.

In the UK, air pollution levels have improved over the past several decades, thanks to initiatives such as the Gothenburg Protocol (implemented through the National Emission Ceilings Directive), the Air Quality Directive of the European Parliament and Council (e.g. 2008/50/EC), and Air Quality Standards Regulations (2010). Reductions in air pollution levels since the 1970s (primarily driven by policy interventions) led to a reduction in UK attributable mortality due to exposure to $PM_{2.5}$ and NO_2 of 56% and 44% respectively (Carnell et al. 2019). In recent years, policy announcements such as the 25-year Environment plan[1] and the Environment Act $PM_{2.5}$ targets are expected to be the dominant driver for policy on air quality. Advancements have also been made in our understanding of how air pollution impacts human health, for example, in respect of quantification of burdens at low concentrations and for pollutant mixtures (COMEAP 2022c; Dominici et al. 2022; HEI 2022; Stafoggia et al. 2022).

To better understand likely future impacts to human health in the UK from changes in air quality, we perform an up-to-date quantitative health impact assessment. We simulate spatial concentrations of surface $PM_{2.5}$ and NO_2 concentrations for present day (taken as 2018) and for 2030, 2040 and 2050 using a high spatial resolution atmospheric chemistry and aerosol model with the latest official UK and European emissions datasets. These are combined with the most recent recommendations on exposure–response relationships from the UK's Committee for the Medical Effects of Air Pollutants (COMEAP), to quantify future changes to mortality burdens from long-term exposure to ambient air pollution in the UK under current emissions policies.

2. Methods

2.1. Air pollution modelling and emissions

Simulations of present-day and future air quality were undertaken at 3 km × 3 km horizontal resolution with the EMEP4UK atmospheric chemistry transport model version rv4.36. EMEP4UK is a nested version, focused on the British Isles (Fig. 1a), of the Convention on Long-range Transboundary Air Pollution (CLRTAP) EMEP MSC-W model described in Simpson et al. (2012), with updates as specified in annual reports (emep.int/mscw). The EMEP4UK model has been widely used to simulate historic, present-day and potential future air quality over the UK (Heal et al. 2013; Nemitz et al. 2020; Vieno et al. 2014; Vieno et al. 2016), including provision of evidence to the UK government (AQEG, 2013, 2017; AQEG, 2021; HPA, 2012). The lowest model layer has a height of 45 m and hourly surface concentrations of air pollutants are adjusted to correspond to 3 m above the surface as described in Simpson et al. (2012). Modelled total $PM_{2.5}$ includes particle-bound water to reflect measurements of $PM_{2.5}$ as defined in UK and European air quality regulations.

The EMEP4UK model was driven by hourly meteorology for 2018 from the Weather Research and Forecasting (WRF) model version 4.2.2 (wrf-model.org, Skamarock et al., 2019) which includes data assimilation (Newtonian nudging) of the numerical weather prediction model meteorological reanalysis from the US National Center for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) Global Forecast System (GFS) at 1° resolution every 6 h (NCAR 2000).

Gas-phase chemistry is simulated using the EmChem19 scheme (Bergström et al. 2022), whilst the aerosol scheme is the Equilibrium Simplified Aerosol Model V4 (EQSAM4clim) (Metzger et al. 2018). Dry deposition of gas and aerosol species is simulated utilizing deposition velocity; for wet deposition, all $PM_{2.5}$ components have the same in-cloud wet scavenging ratio and below-cloud size-dependent collection efficiency by raindrops, whilst coarse particles are divided into coarse sea salt and other coarse particles with their own sets of parameters (Simpson et al. 2012).

For 2018 simulations, anthropogenic emissions for the UK of NO_x, NH_3, SO_2, CO, NMVOC (non-methane volatile organic compounds), $PM_{2.5}$ and PM_{CO} (coarse particulate matter of diameter 2.5 µm to 10 µm) were taken from the National Atmospheric Emissions Inventory (naei.beis.gov.uk). Emissions of isoprene and other biogenic VOC from vegetation, NO_x from lightning and soil, wind-derived dust and sea salt, and marine dimethyl sulphide (DMS), are all linked to the meteorological year and simulated as reported in Simpson et al. (2012) and model update reports specified above. UK emissions for model simulations of atmospheric composition in 2030, 2040 and 2050 use the 'business as usual (BAU)', also referred to as 'baseline', scenarios developed for Defra (ApSimon et al. 2019; Defra, 2022; Oxley et al. 2023). These projections reflect assumed trends under existing interventions and policies relating to air quality, including adjustments for recent policy that had not been incorporated into the 2018 NAEI projections. For the rest of the extended European domain in which the British Isles domain is nested, official EMEP emissions fields for the corresponding years were applied (https://www.ceip.at). More detail on the model emissions and simulations is given in Supplementary Material section S1.

2.2. Population-weighted pollutant concentrations

Annual mean $PM_{2.5}$ and NO_2 concentrations at 3 km spatial resolution were population-weighted to create regional population-weighted exposure estimates for the nine regions in England, and for Scotland, Wales and Northern Ireland (Fig. 1b), using 100 m gridded residential population information for England, Scotland and Wales (National Population Database 2020), and at 1 km for Northern Ireland (Reis et al., 2017).

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[1] https://www.gov.uk/government/publications/25-year-environment-plan.

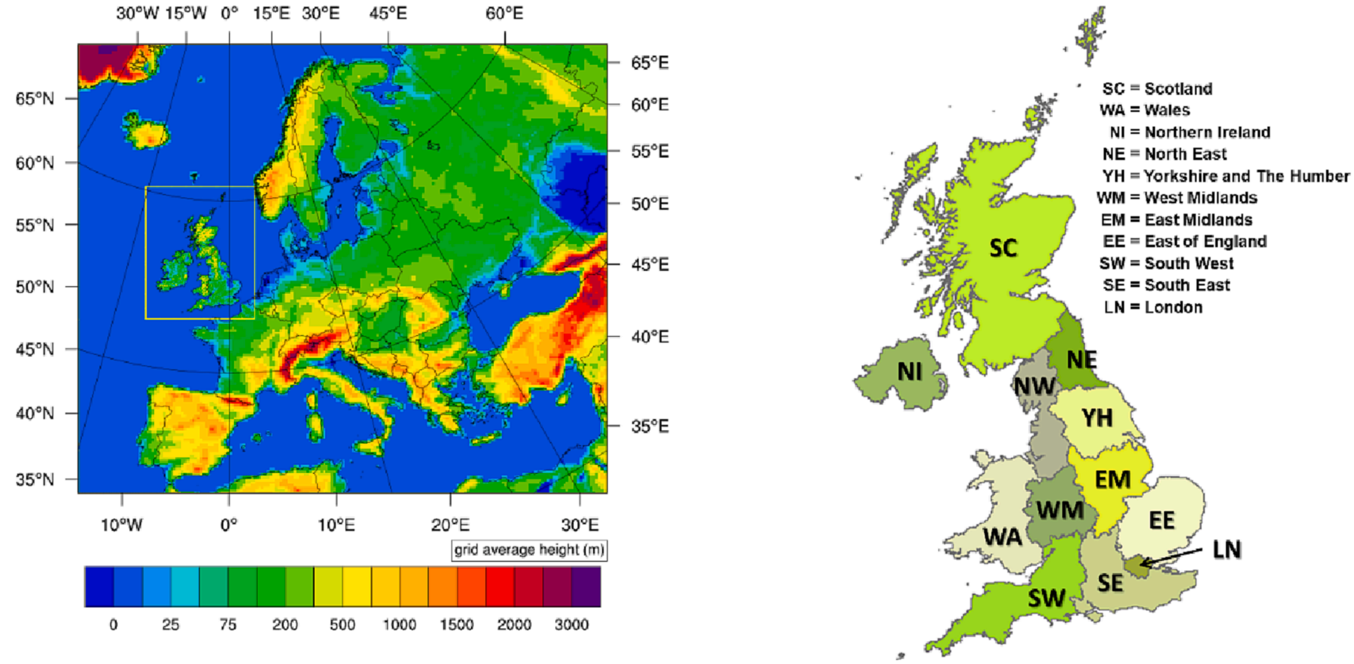

Fig. 1. (a) The EMEP4UK model domain showing the 3 km × 3 km resolution British Isles domain (yellow box) nested within an extended Europe domain at 27 km × 27 km (plotted variable is altitude). (b) Regions used in the health impact assessment analysis. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.3. Health impact calculations

The annual mortality burden attributable to long-term exposure to each air pollutant (M_{aq}) was calculated for each region as follows:

$$M_{aq} = M_T \times AF$$

$$AF = \left(\frac{RR - 1}{RR}\right)$$

$$RR = exp\left(\beta \times \frac{AQ}{10}\right)$$

$$\beta = \ln(ERF)$$

where M_T is the total annual mortality in the region, AF is the attributable fraction of mortality in that region resulting from exposure to the air pollutant, RR is the relative risk of the health outcome, AQ is the population-weighted air pollutant metric and ERF is the exposure–response coefficient (per 10 μg m^{-3}) with β being the slope of ERF.

To estimate the mortality burden arising from simultaneous exposure to $PM_{2.5}$ and NO_2 the method described by COMEAP (2018) was followed. This approach uses the higher of estimates from either $PM_{2.5}$ or NO_2 as the primary indicator of air pollution, by using 'unadjusted' coefficients to capture the effect of air pollution as a whole via single-pollutant analyses. In addition, a combination of paired reductions of the summary coefficients from single-pollutant models for both $PM_{2.5}$ and NO_2 was used for producing mutually adjusted coefficients (i.e. effects of $PM_{2.5}$ adjusted for those of NO_2, and vice versa). Pairs of coefficients from four studies were selected (Beelen et al. 2014; Crouse et al. 2015; Fischer et al. 2015; Jerrett et al. 2013). For each study, the percentage reduction in NO_2 coefficient on adjustment for $PM_{2.5}$ was applied to the unadjusted summary NO_2 coefficient; similarly, the percentage reduction in $PM_{2.5}$ coefficient on adjustment for NO_2 was applied to the unadjusted summary $PM_{2.5}$ coefficient. The estimated mortality burdens obtained using these mutually adjusted summary coefficients were then summed to give an estimated mortality burden of air pollution. Estimates obtained in this way can be compared with those derived using unadjusted coefficients for NO_2 and $PM_{2.5}$.

For impacts on annual all-cause (excluding external causes) mortality, unadjusted exposure–response coefficients of 1.08 (95% CI: 1.06, 1.09) per 10 μg m^{-3} annual mean $PM_{2.5}$, and 1.023 (95% CI: 1.008, 1.037) per 10 μg m^{-3} annual mean NO_2 were used as recommended for the UK by COMEAP (COMEAP, 2018; 2022a). The recent update for $PM_{2.5}$ specifies use of the full $PM_{2.5}$ mass concentration (i.e. no subtraction of any chemical or source component), and an assumption of no threshold below which health effects do not occur. The four pairs of adjusted coefficients are given in supplementary Table S1.

Annual all-cause mortality data was obtained from the UK Office for National Statistics (ONS) for the nine regions in England and Wales (extracted via nomisweb.co.uk), from the National Records for Scotland (NRS) for Scotland (NRS 2019), and from the Northern Ireland Statistical and Research Agency (NISRA) for Northern Ireland (NISRA, 2021), with extraction limited to external causes only (ICD10 codes A00-R99) for those 30 years and older.

Future population change was also included by scaling the HIA results based on population projections from ONS. Results were normalised using the ONS mid-year population estimates for 2018 for each region for those aged 30 years and older (to match the age groups considered in the mortality analysis), and the results scaled for future years using population projections. A range of population projections are produced by ONS for the UK based on assumptions of future fertility, mortality, and migration trends (based on long-term demographic trends), with different scenarios ('variant' projections) produced based on high/low fertility, migration, and mortality. We use here the 'principal' population projections representing a 'middle' estimate for future population demographics (interim 2020-based, ONS, 2022[2]). Projections are available for Scotland, Wales, Northern Ireland, and

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[2] The use of the term "interim" in the 2020 release reflects the interval between the 2020-based principal projection and subsequent projections, which will incorporate Census 2021 data. It also recognises uncertainties in the mid-2020 base year and in setting long-term demographic assumptions following the onset of the coronavirus (COVID-19) pandemic.

England as a whole, so regional totals in England are scaled uniformly. Population totals are shown in Supplementary Table S2.

3. Results

The results of our HIA using unadjusted (single-pollutant) coefficients (and constant population) are shown in Fig. 2. Across the UK, population-weighted regional reductions in $PM_{2.5}$ between 2018 and 2050 range from 28% to 36%, and for NO_2 from 35% to 49% (supplementary Table S3); the greatest absolute reduction occurs in London, and the greatest fractional reduction occurs in East of England (due to the slightly lower background concentrations in this area). Maps of the $PM_{2.5}$ and NO_2 concentrations are presented in the Supplementary Figure S1. The greatest attributable fractions of mortality, where air pollution levels are highest, are in London (LN) and the South East (SE) for $PM_{2.5}$, and in London and the North West (NW) for NO_2 (Fig. 2, left column). The total estimated mortality burden in each region is also affected by mortality rates and population in each region, with the North West, London and South East having larger populations; for example the North West has the sixth highest AF for $PM_{2.5}$ but the second highest mortality burden.

All results from the unadjusted $PM_{2.5}$ and NO_2 calculations, as well as from the analysis using the four sets of paired coefficients (Table S1) are presented in supplementary Tables S4-7 (for constant population). The attributable mortality applying the largest of the individual coefficients and the range of the paired coefficients are summarised in Table 1. Our analysis suggests that for present day (2018), annual mortality attributable to the effects of long-term exposure to $PM_{2.5}$ and NO_2 is 26,287 – 42,442, and that this will be lower by 31%, 35%, and 37% in 2030, 2040 and 2050 respectively (relative to 2018) assuming constant population.

Table 1
Annual mortality range by region, summarising calculations for $PM_{2.5}$ and NO_2 together (assuming constant population).

	Emission year			
Region	**2018**	**2030**	**2040**	**2050**
SC	1648 – 2587	1131 – 1898	1083 – 1823	1075– 1805
WA	1116 – 1987	759 – 1442	721 – 1368	714– 1348
NI	391 – 736	275 – 538	264 – 511	263– 507
EE	2630 – 4384	1738 – 3078	1585 – 2843	1533– 2760
EM	2013 – 3337	1333 – 2328	1244 – 2177	1220– 2129
LN	3398 – 4779	2215 – 3317	2069 – 3115	2028– 3046
NE	942 – 1527	633 – 1099	596 – 1040	588– 1022
NW	3385 – 5299	2235 – 3697	2129 – 3529	2112– 3485
SE	3867 – 6304	2580 – 4420	2365 – 4107	2287– 3993
SW	1952 – 3500	1308 – 2511	1221 – 2367	1196– 2321
WM	2563 – 4122	1659 – 2836	1554 – 2664	1529– 2613
YH	2381 – 3880	1583 – 2716	1488 – 2558	1465– 2511
UK total	**26,287 – 42,442**	**17,449 – 29,879**	**16,321 – 28,104**	**16010– 27,539**
Mid value of the UK range	34,365	23,664	22,213	21,775
% change from 2018	–	−31.1%	−35.4%	−36.6%

Regionally, the South East, North West and London experience the greatest absolute reduction in attributable mortality compared with 2018 (Fig. 3a). The greatest fractional reduction in mortality in 2030 is in the West Midlands, whilst by 2050 the greatest fraction reduction is in the East of England (Fig. 3b). Reductions in mortality in Northern Ireland, North East, Wales and Scotland are smaller, due to both smaller populations and generally lower levels of $PM_{2.5}$ and NO_2.

The impact of population projections (which increase the total

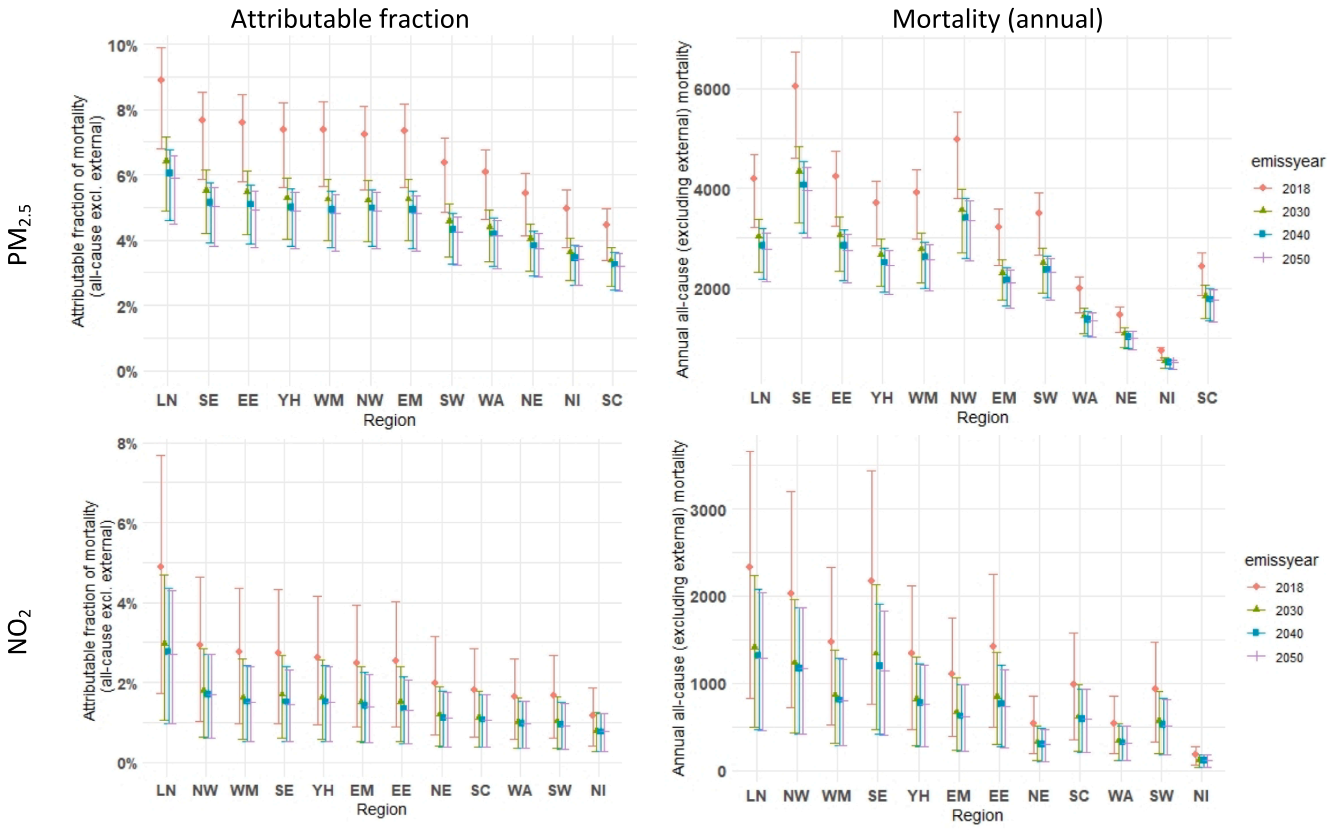

Fig. 2. Regional attributable fraction of mortality (left column) and annual mortality (right column) associated with long-term exposure to $PM_{2.5}$ and to NO_2 for 2018, 2030, 2040 and 2050. For each pollutant, regions are ordered in descending order of attributable fraction of mortality. Uncertainty bars represent the 95% CI on the exposure–response coefficient. Results for each pollutant are derived from unadjusted coefficients and should not be summed to represent the total health burden. See Fig. 1b for region codes.

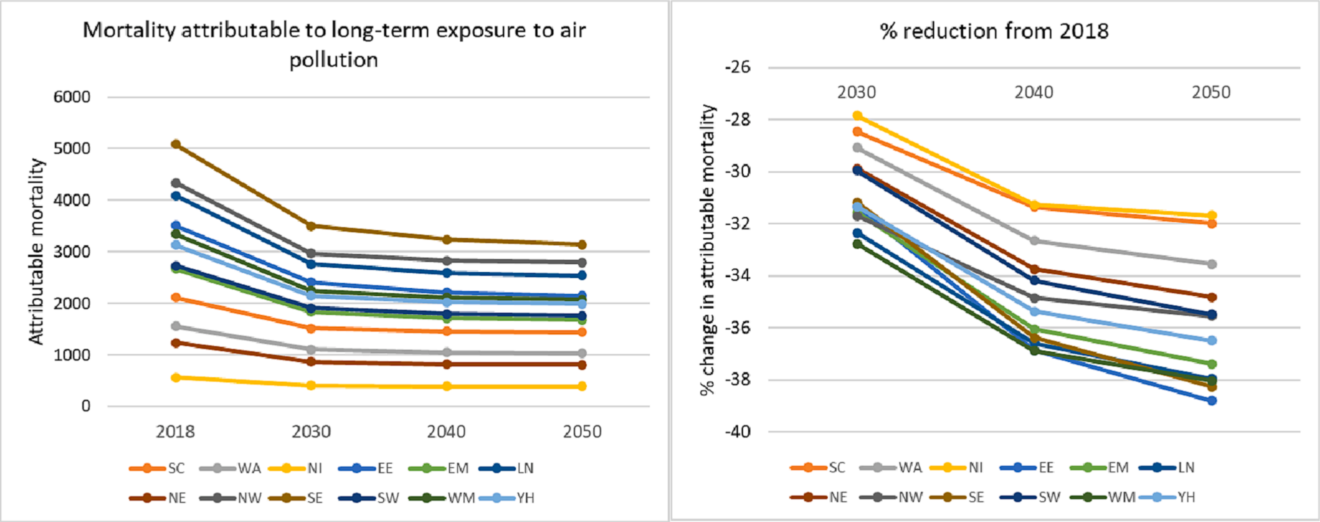

Fig. 3. (left) Annual attributable mortality by region in the UK for 2018, 2030, 2040 and 2050. Values are the middle of the ranges shown in Table 1; (right) Fractional reduction in attributable mortality compared to 2018.

population) leads to an increase in the absolute projected mortality burdens (Table 2). Projected populations increase most in England (17.7% by 2050), least in Scotland (9.2%), and by about 15% in both Wales and Northern Ireland (Table S2). The estimated health burdens in the future years increase by corresponding amounts (Table 2), which moderates the anticipated reductions in future. With no population changes, mortality due to long-term effects from $PM_{2.5}$ and NO_2 air pollution are projected to be lower by 31%, 35%, and 37% in 2030, 2040 and 2050 respectively (relative to 2018), but when population growth is included, corresponding values are reductions of 25%, 27%, and 26% respectively. This assumes the mortality rates in those over 30 do not change in the future.

4. Discussion

Our results suggest that current policies driving emission reductions will lead to improvements in NO_2 and $PM_{2.5}$ air quality and substantial reductions in the burden of associated chronic health impacts in the UK: of the order of 31% reduction in impacts for 2030 and 36% for 2050 compared with a 2018 baseline (Fig. 2, Table 1). Increases in mortality due to increased population in future years will, however, moderate the reduction in absolute mortality associated with the pollution concentration reductions (Table 2), to reductions of 25%, 27% and 26% in 2030, 2040, and 2050 respectively, in line with previous studies (Fenech et al. 2021; Silva et al. 2016). The discussion here focuses on the health benefits directly associated with the emissions reductions (constant population assumption).

Our analysis for current impacts (2018) compares well with another recent evaluation; we estimate annual mortality attributable to long-term exposure to air pollution of 26,287 – 42,442 deaths annually, compared with 29,000 – 43,000 from Mitsakou et al. (2022), who used a slightly different emission year and different air pollution simulation. Our results for future years are also comparable to previous studies examining health impacts associated with air pollutant emission changes associated with RCP scenarios (Fenech et al. 2021), though there are some differences in terms of emission scenarios used, model resolution (which can impact fine-scale chemical processes), and health impact assessment methodology.

The absolute and fractional changes in health impacts vary regionally across the UK due to a combination of differing regional air pollution levels, baseline mortality rates, and regional population. Regional population-weighted NO_2 concentrations reduce by a greater fraction than do $PM_{2.5}$ concentrations (35% to 49% reduction for NO_2, compared to 28% to 36%), primarily due to emission controls on vehicle emissions, which are close to population centres.

Our analysis provides quantitative estimates of the potential future benefits to health of current policy commitments, though as there is no threshold for effect, health impacts associated with chronic exposure to air pollution will remain in future, albeit significantly reduced. Recent studies have shown that exposure even to low concentrations of air pollution leads to adverse health effects (Brauer et al. 2022; Brunekreef et al. 2021; Dominici et al. 2019). In response to the new evidence, WHO have updated their air quality guidelines to a guideline concentration for $PM_{2.5}$ of 5 µg m^{-3} annual mean (reduced from the 10 µg m^{-3} value published in 2005, now considered an interim target value), and a guideline concentration for NO_2 of 10 µg m^{-3} annual average (reduced from the previous 40 µg m^{-3}) (World Health Organization, 2021c). Our analysis suggests that regional population-weighted concentrations in 2050 (Table S3) will reach the new WHO guideline value for $PM_{2.5}$ of 5 µg m^{-3} annual mean only in Northern Ireland, Scotland and the North East; however, for the new guideline value for NO_2 of 10 µg m^{-3} annual average, this will be met in all regions except London (Table S3). Our results on meeting WHO target and guideline values compare well with estimates from a recent report (using similar emissions but different

Table 2
Annual mortality range, using 'middle' estimates of future population reported in recent ONS 2020-based projections (see main text for further details).

Emissions year	Population (>30 yrs old)	Annual Mortality long-term, UK total			
2018	42.1 m	26,287 – 42,442			
		with static population	with projected population	% change in the given year due to increasing population	% change from 2018 with new population changes included
2030	45.6 m	17,449 – 29,879	18,887 – 32,342	+8.2%	−25.4%
2040	47.4 m	16,321 – 28,104	18,384 – 31,657	+12.6%	−27.2%
2050	49.2 m	16,010 – 27,539	18,732 – 32,220	+17.0%	−25.9%

modelling methods), with all regions reaching the 10 μg m^{-3} interim target by 2030 (apart from some kerbside locations in London) (Dajnak et al. 2022). However, it should be noted that the results we present are population-weighted regional concentrations, and pollutant concentrations at specific locations will vary. Significant further efforts will likely be required to meet the new WHO guideline value for $PM_{2.5}$ of 5 μg m^{-3} annual mean; it is unclear how feasible attainment of this will be when considering the contribution of non-anthropogenic pollution sources and transboundary pollution (Pai et al. 2022). The emissions used in this study represent projections based on current legislation and trends (Supplementary Section S1) and further commitments may be required to meet any new air pollution reduction targets. Of course, any additional future reductions in $PM_{2.5}$ and NO_2 concentrations beyond those simulated here will bring further benefits to health beyond those presented in this study. It is also important to recognise that the simulations of future air pollution levels in the UK assume that emissions elsewhere in Europe follow the projections used here; they may reduce more or less than assumed here, and the impact of these emission changes will be greatest in the south-east of the UK. Climate change will also act on many processes controlling surface concentrations of $PM_{2.5}$ and NO_2 concentrations but it is not yet possible to include all these climate-associated processes in models at the spatial and temporal resolution required for health impact assessments. As discussed above, where studies of future air quality have endeavoured to include some impacts of climate change it has been found that changes in air quality due to anthropogenic emission changes dominate over those due to climate change (Doherty et al. 2017).

Shifting sources of air pollution in future (for example in response to air quality and climate change policies and associated actions and technologies) will mean the air pollution mixture will likely change over time, and exposure–response coefficients derived from the existing pollutant composition may also change, but it is not possible to predict future changes in exposure–response relationships. Additionally, there may be future changes in underlying health status of the population, as well as demographic changes. There are still many unknowns around differential toxicity of particles (COMEAP, 2022b), and this remains an important area for future epidemiological research.

The methods here use a simple burden calculation to estimate health effects, but follows UK recommendations, meaning that the calculated annual health burden is estimated assuming that the population is exposed to a particular level of pollution over the life course. It is likely that improvements in air quality will happen over time, though the specific impacts will depend on the speed and scale of emission reductions. Our results indicate the likely impacts to health if emissions likely to be reached at a particular indicative year in the future were to be met and sustained. Relevant to this, we note that the majority of the gain in health that we estimate is achieved early on in the 2030 to 2050 future timeline simulated. Here we use a burden calculation based on the latest recommendations from COMEAP, specific to the population under consideration (UK), and the use of detailed atmospheric chemistry composition modelling at relatively fine spatial scale is advantageous for better capturing non-linear chemistry effects and characterising population exposure. Other health impact assessment methods are also in use (e.g. Burnett et al., 2018; Hassan Bhat et al., 2021; Khomenko et al., 2021) using different exposure-mortality models and other health outcomes. Other metrics are also used, for example mortality burden is sometimes quantified in terms of years of life lost, a metric that includes information on the age of the population and survival rates considering the air pollution exposure. In this study we performed a simple sensitivity analysis by scaling the results based on projected population changes (while assuming no changes in underlying mortality rates), in addition to our quantification based on unchanged population. Potential changes in baseline mortality rates are another source of uncertainty for future projections, though these are challenging to predict and not considered here. The effects of higher air pollution levels and air pollution episodes will also undoubtedly be modified by behaviours that affect exposure, such as time indoors and exercise, which may affect inhalation.

5. Conclusion

We have modelled the impacts of current emission policies on future $PM_{2.5}$ and NO_2 concentrations, and used a health impact assessment to estimate the impacts of these pollutants on mortality across the UK. Mortality burdens in future will be substantially reduced following current policies driving emission reductions, being lower by 31%, 35%, and 37% in 2030, 2040 and 2050 respectively (from 26,287 – 42,442 deaths annually for 2018), assuming no population changes, with greatest reductions seen in London and the South East. When accounting for projected increases in population, the benefits to health are somewhat diminished, resulting in reductions of 25%, 27%, and 26% in mortality burdens for 2030, 2040, 2050 respectively, demonstrating that improvements in overall burdens may be overestimated where population growth is not accounted for.

Significant reductions in future mortality burdens are estimated, demonstrating the substantial benefits to health of emission reduction policies, providing detailed quantitative estimates valuable for understanding policy impacts. Despite this, effects of air pollution on health are not eliminated, and further efforts are likely needed to reduce health impacts of air pollution. As emission sources change, future work should consider any further developments in the evidence related to differential toxicity of particles, as well as future population changes.

CRediT authorship contribution statement

Helen L. Macintyre: Conceptualization, Methodology, Data curation, Formal analysis, Visualization, Writing – original draft. **Christina Mitsakou:** Conceptualization, Methodology, Formal analysis, Supervision, Writing – original draft. **Massimo Vieno:** Methodology, Data curation, Formal analysis, Software, Writing – review & editing. **Mathew R. Heal:** Conceptualization, Methodology, Formal analysis, Writing – review & editing. **Clare Heaviside:** Conceptualization, Methodology, Writing – review & editing. **Karen S. Exley:** Writing – review & editing.

Declaration of Competing Interest

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

Data availability

The authors do not have permission to share data.

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Appendix A. Supplementary material

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