Bristol City Health and Economic Impact Assessment study

For: UK:100

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1.0 Executive Summary and Key results

UK100 commissioned the Environment Research Group (ERG) at Kings' College London (King's) to produce a health and economic impact assessment associated with current[1] and future pollution concentrations in Bristol City. ERG has previously carried out similar health impact calculations for London, Greater Manchester, Birmingham City and Liverpool City Region, but to our knowledge this is the first time that the new health impact recommendations (COMEAP, 2018a)[2] have been applied in practice to the largest city in the South West of England – Bristol – using the NAEI 2017 $PM_{2.5}$ and NO_2 concentrations projected to 2030[3].

Mortality impact (long –term exposure)
The population in Bristol would gain around 150,000 life years over a lifetime to 2134[4] if air pollution concentrations improved as projected from 2011 to 2030[5], compared with remaining at 2011 concentrations. The average life expectancy of a child born in Bristol in 2011 would improve by around 2 to 3 months for the same comparison.

Taking into account the UK Government's projected future changes in air pollution concentrations from 2011 to 2030, the population would still be losing between 90,000 to 300,000 life years in Bristol (a life year is one person living for one year). Put another way, children born in 2011 are still estimated to die 1.5-6 months early[6] on average, if exposed over their lifetimes to the projected future air pollution concentrations in Bristol. Males are more affected than females, and this is due to the fact that men have higher death rates and die earlier than women.

The report provides figures for both $PM_{2.5}$ and NO_2 separately but then uses one or the other as the best indicator pollutant rather than adding results together to avoid large overestimation of the mortality impact of air pollution (details in the report below). The 'best indicator' approach may result in a small underestimate.

Economic costs
The monetised benefits over a lifetime[7] of improvements to future anthropogenic $PM_{2.5}$ and NO_2 concentrations, compared with 2011 concentrations remaining unchanged, has been estimated to be up to £80 million on average/year (at 2014 prices).

Despite the projected future improvements in air pollution concentrations from 2011 to 2030, the economic health impact costs in Bristol over a lifetime are still between £50 - £170 million on average per year.

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[1] Air quality annual status and air quality plan reports show that some parts of Bristol have been in breach of both the national air quality objective for NO_2 and the World Health Organisation guideline for $PM_{2.5}$.
https://www.cleanairforbristol.org/wp-content/uploads/2019/09/Bristol_City_Council_2019_ASR_v1.pdf
https://www.cleanairforbristol.org/what-we-are-doing/what-is-bristol-city-council-doing-about-it/
[2] COMEAP – the Committee on the Medical Effects of Air Pollutants is a national expert Committee advising Government on the health effects of air pollution. Their recommendations for quantification are usually used in Government cost-benefit analysis of policies to reduce air pollution.
[3] https://uk-air.defra.gov.uk/data/laqm-background-maps
[4] It is not possible to calculate the full result for gains in life expectancy until everyone in the initial population has died (105 years from 2030), necessitating follow-up for a life-time even if the pollution changes are only for the next decade or so.
[5] 2011 and 2017 concentrations representing current reference years and any future years up to 2030 have been estimated from the 2017 baseline.
[6] The range is according to whether indicator pollutant is taken as $PM_{2.5}$ or NO_2, whether or not there is a cut-off concentration below which no effects are assumed and gender.
[7] From 2030, so the total time period was 2011-2134.

These are what is called 'annualised' figures - a term for an average per year when the result is not the same every year. Economists assign monetary values to the health benefits of reducing air pollution in cost-benefit analysis in order to compare with the costs of implementing a package of policies. The monetary value for each individual health outcome is then added up across time, people and the total health effects. They are not actual costs but a measure of the amount of money society believes it would be reasonable to spend on policies to reduce air pollution[8] (to avoid the adverse health effects of the remaining pollution) or was reasonable to have spent on policies that have already reduced air pollution.

Mortality burden (long –term exposure)

Mortality burden calculations are a simplified calculation at one point in time. They are not suitable for analysing several years in succession because they do not have a mechanism for allowing the number of deaths the year before to influence the age and population size the following year (lifetables do this, see impact calculations above). Nonetheless, they provide a useful feel for the size of the air pollution problem.

In 2011 in Bristol the equivalent of[9] between 200 to 260 deaths are estimated to be attributable to anthropogenic $PM_{2.5}$ and NO_2. These deaths occur mostly at older ages, as is typical for deaths in the general population.

The results varied by constituency with the highest in Bristol North West and the lowest in Bristol West. The ranking by constituency did not follow the ranking in pollutant concentrations. This is because the results are also influenced by variations in death rates by constituency, which in turn are driven in part by the proportion of elderly in the population and the level of deprivation.

Impact of Air Pollution on inequalities, ethnic groups, population change, migration and students

Although Bristol is considered to be one of the relatively less deprived English core cities, Bristol deprivation 'hot spots' are amongst some of the most deprived in the country. Overall, Bristol does not particularly show environmental inequality (in which socioeconomically disadvantaged populations are among the most exposed), except for the area of Lawrence Hill identified as having both some of the highest levels of deprivation and air pollution in Bristol as well as by far the highest Black and Minority Ethnic population in Bristol.

The highest concentrations of $PM_{2.5}$ and NO_2 air pollution in Bristol have been found to coincide with areas of exceptional population growth (70% population change between 2007 and 2017 in Central, 55% in Hotwells & Harbourside and 39% in Lawrence Hill wards), areas where most recent migrants tend to live (in inner city areas of Bristol in particular in Central and Lawrence Hill wards and some part of Hotwells & Harboursidse) and areas where most students live during term time (including Central, Cotham, Clifton Down, Hotwells and Harbourside and Clifton wards).

[8] The monetary value comes from a survey asking 170 members of the public how much they would be willing to pay to reduce their risk of experiencing a loss of one month of life (in good health) due to air pollution. NHS costs and loss of productivity are not included.

[9] The original studies were analysed in terms of 'time to death' aggregated across the population. Strictly, it is unknown whether this total change in life years was from a smaller number of deaths fully attributable to air pollution or a larger number of deaths to which air pollution partially contributed. The former is used with the phrase 'equivalent' to address this issue. See COMEAP (2010) for a fuller discussion.

This study shows that adverse health impacts remain and that further pollution improvements beyond those already made are still needed. All Bristol citizens would benefit greatly from a reduction in air pollution concentrations.

Comparison with results for Liverpool City Region (LCR), Greater Manchester (GM) and Birmingham City

The results for life years lost (after pollution improvements) and attributable deaths (from 2011) in Bristol were smaller than the results in Liverpool City Region, Birmingham city and Greater Manchester. Bristol has a lower death rate (1.28%) than LCR (1.49%), Birmingham (1.33%) and GM (1.36%) but these results can be explained primarily by the population in Bristol (around 0.5 million) being much smaller than LCR (1.5 million), Birmingham (1 million) and GM (2.7 million). In addition, Bristol has lower NO_2 concentrations than Birmingham and GM and lower $PM_{2.5}$ concentrations than Birmingham, further explaining the lower results in comparison with these cities. Bristol does have higher NO_2 concentrations than LCR and higher $PM_{2.5}$ concentrations than LCR and GM but not to a sufficient extent to counteract the influence of its lower population and death rate i.e. the results are still lower overall despite the higher pollution concentrations in some cases.

The loss of life expectancy (which is independent of population) is close between the four cities/region of interest and somewhat follows the ranking order of the $PM_{2.5}$ and NO_2 concentrations. Gains in life years are smaller in Bristol than in the other three cities/region of interest, again mainly due to differences in population size and the ranking across the cities in the size of the reduction in pollution concentrations over time.

Limitations

The main report presents a wider range of uncertainty around the results for the mortality burden, mortality impacts and economic costs than the figures shown here.

The study was focused on air pollution changes within Bristol. Reductions in emissions will also have benefits for air pollution concentrations in the wider region (South West England and beyond). For example, reductions in NO_x emissions will reduce nitrate concentrations and thus $PM_{2.5}$ concentrations in the wider region. The health benefits of this are not reflected here, although they are likely to be smaller than those in Bristol itself.

There will be further impacts from ozone concentrations. The long-term ozone exposure (representative of summer smog ozone concentrations metric) is projected to decrease over time compared with 2011 but less than other pollutants such as NO_2 and $PM_{2.5}$.

This study addressed the effect of air pollution on deaths and loss of life-expectancy. This included all causes of death grouped together so covers, for example, respiratory, lung cancer and cardiovascular deaths for which there is good evidence for an effect of air pollution. It does not, however, cover the effect of air pollution on health where this does not result in death. So well established effects (such as respiratory and cardiovascular hospital admissions, effects on asthma, low birth weight etc) and other outcomes more recently potentially linked with air pollution (such as dementia) are not included. Their inclusion would increase the benefit of policies to further reduce air pollution.

2.0 Introduction

UK100 commissioned the Environment Research Group (ERG) at King's College London (King's) to help produce a health impact and economic assessment associated with air pollution levels of Bristol City, the largest city in the South West of England, formed of four parliamentary constituencies (Bristol East, Bristol North West, Bristol South and Bristol West). In order to do that, ERG first downloaded the air pollution data in Bristol City, which then, combined with relationships between concentrations and health outcomes, were used to calculate the impacts on health from the air pollution emitted in each constituency.

3.0 Method

3.1 Air Quality data

From 1kmx1km grid data to ward concentration

Maps of particulate matter with diameter <2.5 μm ($PM_{2.5}$) and nitrogen dioxide (NO_2) annual average concentration were produced for Bristol City. To do this, ERG downloaded $PM_{2.5}$ and NO_2 air pollution data for the regions of 'Southern England' from the DEFRA Local Air Quality Management webpages (https://uk-air.defra.gov.uk/data/laqm-background-maps). The 2011 data were downloaded from the 2011 model predictions, and the 2017 to 2030 data were downloaded from the newly released 2017 model predictions. Using these data of regular 1km by 1km pollutant points we then created a raster layer (for every year and pollutant) using the R statistical analysis package. Mean spatially-weighted concentrations for each Ward were then calculated, using the Ward boundaries from the Governments Open Data portal (http://geoportal.statistics.gov.uk/datasets/wards-december-2016-generalised-clipped-boundaries-in-the-uk).

From ward to population-weighted constituency concentration

Population-weighting average concentration (PWAC): Population-weighting was done at ward level. The ward concentrations were multiplied by the population aged 30 plus for each gender and the resulting population-concentration product summed across all wards in each constituency and then divided by the constituency population. The constituency population-weighted means were then used directly in the health impact calculations across all four constituencies (This process allows one health calculation per constituency rather than calculations in each separate ward). A map of Bristol parliamentary constituencies and wards boundaries can be found in Figure 1.

3.2 Health assessment

It is now well established that adverse health effects, including mortality, are statistically associated with outdoor ambient concentrations of air pollutants. Moreover, toxicological studies of potential mechanisms of damage have added to the evidence such that many organisations (e.g. US Environmental Protection Agency; World Health Organisation, COMEAP) consider the evidence strong enough to infer a causal relationship between the adverse health effects and the air pollution concentrations.

The concentration-response functions used and the spatial scales of the input data is given in Table 13, Table 14 and Table 15 in the Appendix. The concentration-response functions are based on the latest advice from the Committee on the Medical Effects of Air Pollutants in 2018 (COMEAP, 2018a). Previously, burden calculations were based only on concentrations of $PM_{2.5}$ (COMEAP, 2010). The new COMEAP report considers whether there is an additional burden or impact from nitrogen dioxide or other pollutants with which it is closely correlated.

Results are given with and without a cut-off[10] of 7 $\mu g\ m^{-3}$ for $PM_{2.5}$ and 5 $\mu g\ m^{-3}$ for NO_2.

This study uses this epidemiological evidence to estimate the health impacts of the changes in air pollutant concentrations discussed in the air quality modelling section below.

3.3 Economic assessment

Economists assign monetary values to the health benefits in order to compare the benefits with the real costs of implementing a package of policies. The largest proportion of the monetary value comes from a survey asking 170 members of the public how much they would be willing to pay to reduce their risk of experiencing a loss of one month of life (in good health) due to air pollution (Chilton et al, 2004). Added up across time, people and the total health effects, this is then used to represent the amount society thinks should be spent to reduce these risks. NHS costs and loss of productivity are not included.

In undertaking a valuation in monetary terms of the mortality impacts described in the previous section, we have used the methods set out in an earlier report from ERG on the health impacts of air pollution in London (Walton et al., 2015) and in an ERG project funded by NIHR and reported in their journal library (Williams et al., 2018b). This built on previous work by the study team for Defra and the Inter-departmental Group on Costs and Benefits (IGCB) within the UK government. The methods are therefore consistent with those used in government in the UK.
Life years lost were valued using values recommended in Defra guidance[11], updated to 2014 prices. Consistent with this guidance, values for future life years lost were increased at 2% per annum, then discounted using the declining discount rate scheme in the HMT Green Book.[12] The economic impact was then annualised back to 2014, i.e. divided by the total number of years but front-loaded to take into account that benefits accrued sooner are valued more than those accrued later.

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[10] Cut-off is a term used for the concentration below which it is unclear whether or not epidemiological evidence supports the existence of an effect. This does not mean there is no effect below the cut-off, just that the numbers of data points are too small to be sure one way or the other.
[11] Defra (2019) Impact Pathways Approach Guidance for Air Quality Appraisal
[12] HM Treasury (2018) The Green Book

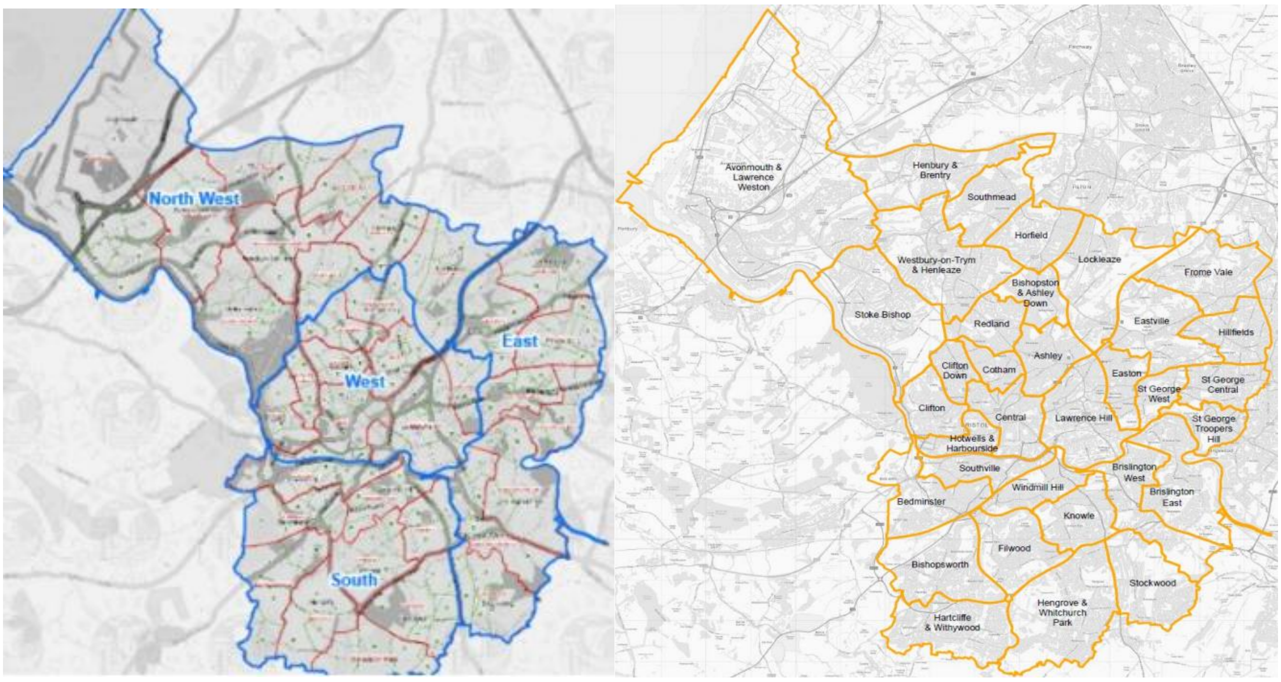

Figure 1 Map of Bristol's parliamentary constituencies (Bristol East, Bristol North West, Bristol South and Bristol West)[13] and Wards[14] boundaries

[13] https://www.bristol247.com/news-and-features/news/general-election-2015-1428602774/
[14] https://www.bristol.gov.uk/documents/20182/436737/Hartcliffe+and+Withywood.pdf/49d31847-00da-471c-95c8-82630662e073

4.0 Air Quality modelling

Bristol city air quality annual status[15] and air quality plan[16] reports show that some parts of Bristol have been in breach of both the national air quality objective for NO_2 and the World Health Organization (WHO) guideline for $PM_{2.5}$. Epidemiological evidence shows that heath impacts are still seen at concentration below the limit values and WHO guidelines. Tackling pollutant emission sources is therefore essential to improve air quality to meet both the UK limit values and the WHO guidelines, and ultimately to achieve the lowest possible levels of pollution.

2011 and 2017 concentrations representing current reference years and any future years in 2020, 2025 and up to 2030 have been estimated from the 2017 baseline[17]. A summary of the population-weighted average concentration (PWAC) between 2011 and 2030 in each constituency is shown in Table 1 and Table 2 for anthropogenic $PM_{2.5}$ and NO_2, respectively. Maps of Bristol city total[18] $PM_{2.5}$ and NO_2 annual mean concentration by wards are shown in Figure 2 and Figure 3, respectively. The reader should refer to the Background Maps User guide (https://laqm.defra.gov.uk/review-and-assessment/tools/background-maps.html#about) for information on an estimated breakdown of the relative sources of pollution and on how pollutant concentrations change over time.

Table 1 Anthropogenic $PM_{2.5}$ PWAC (in µg m^{-3}) (annual) by constituency

Constituency	2011	2017	2020	2025	2030
Bristol East	11.76	9.59	9.17	8.74	8.71
Bristol North West	11.53	8.76	8.35	7.92	7.88
Bristol South	11.14	8.92	8.51	8.08	8.05
Bristol West	12.79	9.46	9.03	8.59	8.56

Table 2 NO_2 PWAC (in µg m^{-3}) (annual) by constituency

Constituency	2011	2017	2020	2025	2030
Bristol East	20.48	16.30	14.45	11.98	10.55
Bristol North West	21.18	14.95	13.20	10.95	9.66
Bristol South	18.06	13.67	12.08	10.04	8.89
Bristol West	27.21	19.69	17.43	14.43	12.74

[15] https://www.cleanairforbristol.org/wp-content/uploads/2019/09/Bristol_City_Council_2019_ASR_v1.pdf
[16] https://www.cleanairforbristol.org/what-we-are-doing/what-is-bristol-city-council-doing-about-it/
[17] Note that the government data projections to 2030 were produced before the Bristol Clean Air Zone was proposed. https://bristol.citizenspace.com/growth-regeneration/traffic-clean-air-zone/
[18] Total air pollution concentration instead of subset air pollution data such as secondary, residual concentrations…

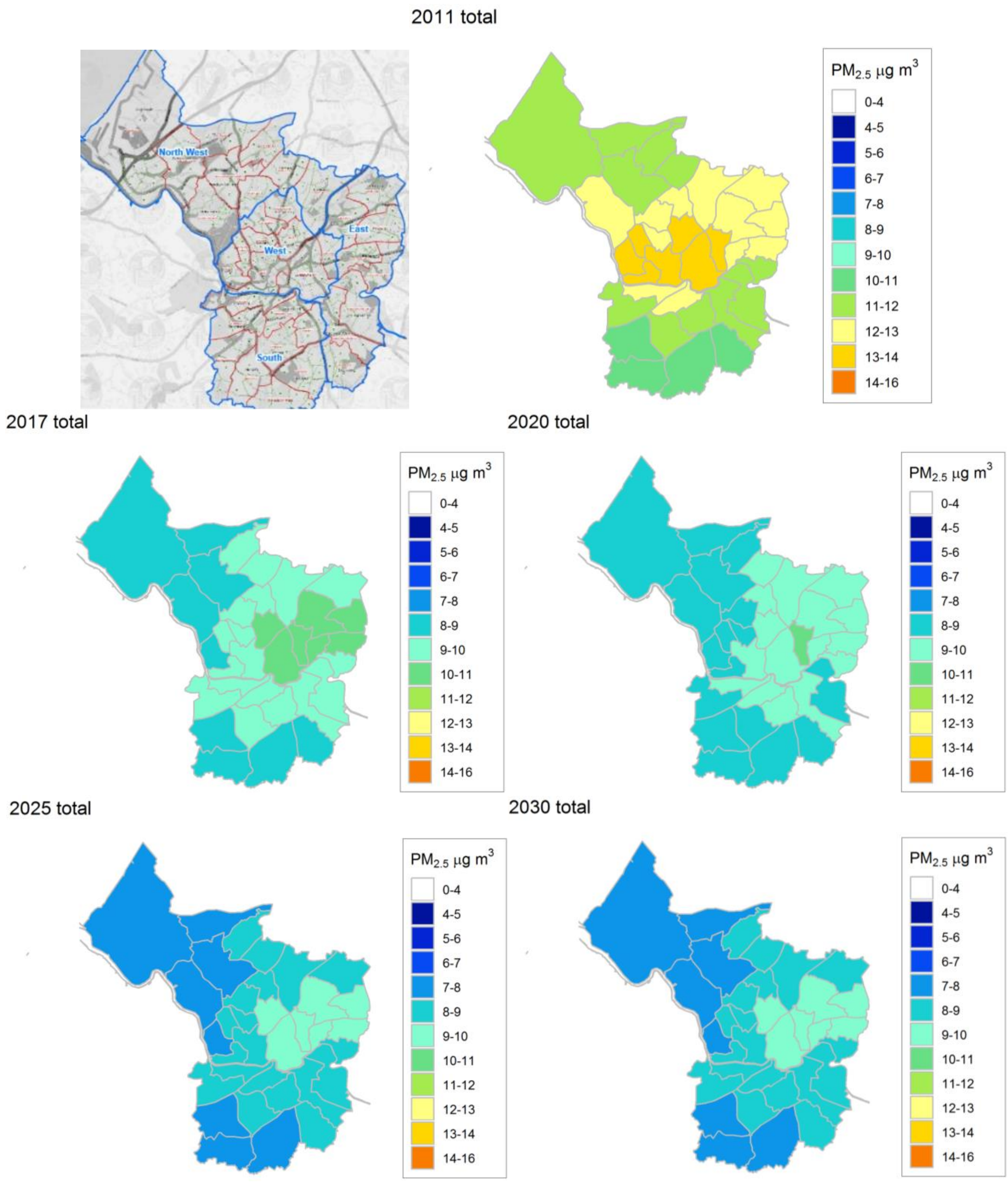

Figure 2 Annual mean $PM_{2.5}$ concentrations (in µg m^{-3}) by wards between 2011 and 2030

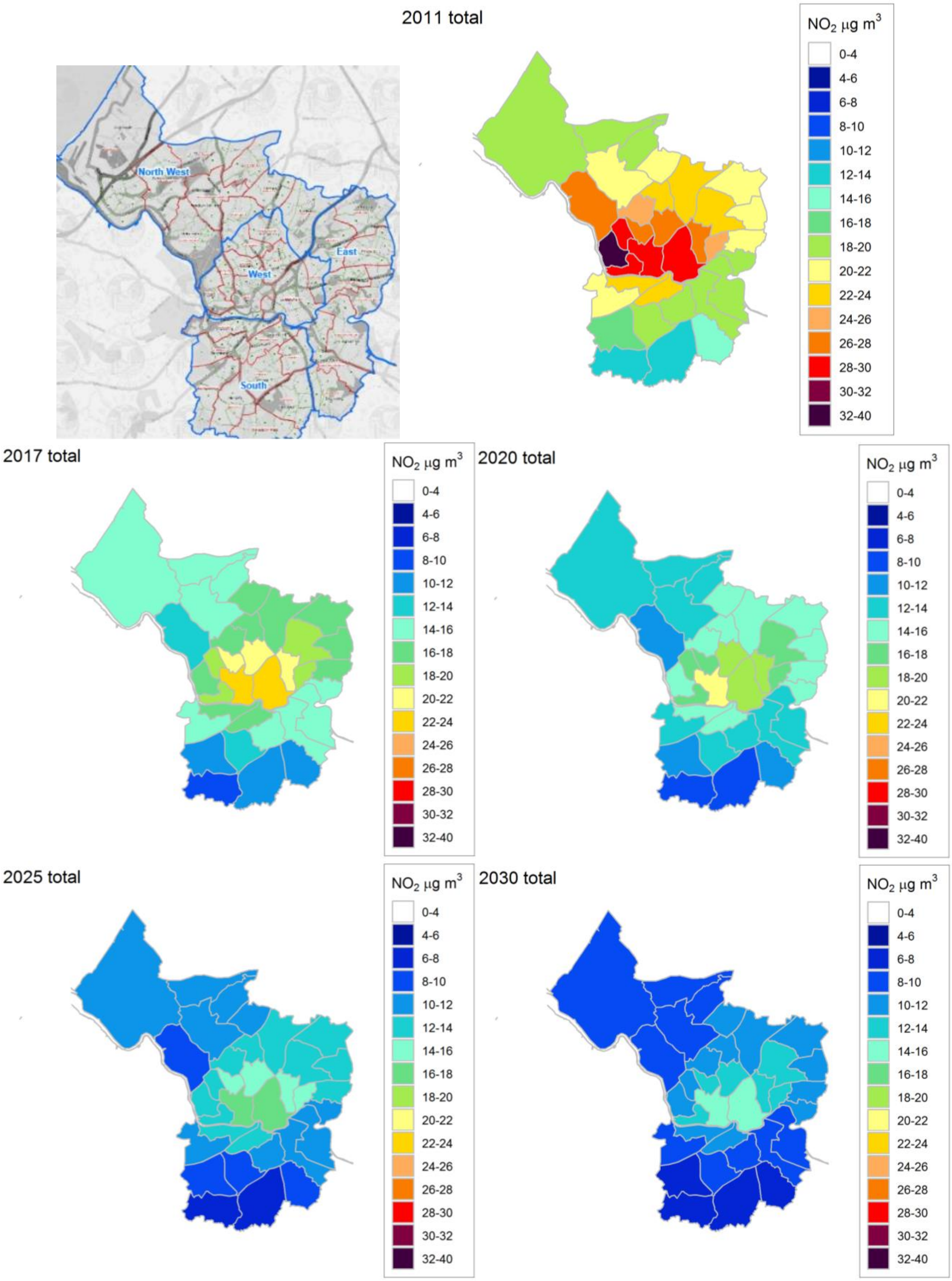

Figure 3 Annual mean NO_2 concentrations (in µg m^{-3}) by wards between 2011 and 2030

5.0 Health Estimates of the mortality impact of air pollution and its economic valuation

5.1 Mortality impact

Impacts in the next section are all expressed in terms of life years – the most appropriate metric for the health impact of air pollution concentration changes over time. This used a full life-table approach rather than the short-cut method used for burden and the data for these calculations had already been incorporated for previous work (Williams et al., 2018a).

Calculations are first given for $PM_{2.5}$ and NO_2 separately. Because air pollutants are correlated with each other, the air pollutant concentrations in the health studies represent both the pollutants themselves but also other air pollutants closely correlated with them. Health impacts from changes in $PM_{2.5}$ and NO_2 represent the health impacts of changes in the air pollution mixture in slightly different ways that overlap i.e. they should not be added. This is discussed further at the end of this section.

The results from the life table calculations assuming that the concentration does not reduce from 2011 levels and assuming the predicted concentration between 2011 and 2030 (concentrations were modelled at 2011, 2017, 2020, 2025 and 2030 but also interpolated for the intervening years) are shown in Table 3, for anthropogenic $PM_{2.5}$ and NO_2. Results for each constituency can be found in the Appendix in Table 16 and Table 20 (life table calculations for anthropogenic $PM_{2.5}$ with and for $PM_{2.5}$ without a cut-off), in Table 17 and Table 21 (life table calculations for NO_2 with and without a cut-off) and Table 18 and Table 19 (central and lower/upper CI estimates of annualised economic impact for anthropogenic $PM_{2.5}$ and NO_2 without a cut-off) and Table 22 (central estimates of annualised economic impact for $PM_{2.5}$ and NO_2 with a cut-off).

The life years lost gives a large number because the life years (one person living for one year) is summed over the whole population in Bristol over 124 years. For context, the total life years lived with baseline mortality rates is around 80 million, so these losses of life years involve about 0.5% of total life years lived.

If 2011 concentrations of anthropogenic $PM_{2.5}$ remained unchanged for 124 years, around 180,000 – 420,000 life years would be lost across Bristol's population over that period. This improves to around 60,000 – 300,000 life years lost with the predicted concentration changes between 2011 and 2030 examined here.

Another way of representing the health impacts if air pollution concentrations remained unchanged (in 2011) compared with the projected future changes (2011 to 2030) is provided by the results for NO_2. If 2011 concentrations of NO_2 remained unchanged for 124 years, around 230,000 – 300,000 life years would be lost across Bristol's population over that period. This improves to around 90,000 – 150,000 life years lost with the predicted concentration changes between 2011 and 2030 examined here.

Summarising these results is not easy. The results should not be added as there is considerable overlap. On the other hand, either result is an underestimate to some extent as it is missing the impacts that are better picked up in the calculations using the other pollutant. COMEAP (2017,

2018a) suggested taking the larger of the two alternatives in the calculation of benefits. We have interpreted this as the larger of the two alternatives in the case of each calculation. Note that this means that the indicator pollutant changes in different circumstances. In the case above, for no cut-off, this is the result for $PM_{2.5}$ (300,000 vs 150,000 life years lost for NO_2). However, for the cut-off, this is the result for NO_2 (90,000 vs 60,000 life years lost for $PM_{2.5}$). Other interpretations e.g. keeping the same indicator pollutant with and without a cut-off, are possible. All the relevant data are in the tables to enable creation of summaries in a different form.
So, the **overall summary** for the projected future changes in air pollution concentrations from 2011 to 2030 would be around **90,000 to 300,000 life years lost** for the population of Bristol over 124 years.

Table 3 Total life years lost across Bristol City population for anthropogenic $PM_{2.5}$ and NO_2 and the associated annualised economic impact (central estimate)

Pollutant	Scenario	Life years lost Central estimate (without cut-off with cut-off)	Annualised economic impact (in 2014 prices) (without cut-off with cut-off)
Anthropogenic $PM_{2.5}$ (representing the regional air pollution mixture and some of the local mixture)	Concentration does not reduce from 2011 levels	415,747 180,004	£234,138,912 £101,281,417
	Predicted concentration between 2011 and 2030	**297,060** 57,453	**£168,836,821** £33,905,354
NO_2 (representing the local mixture and the rural air pollution mixture)	Concentration does not reduce from 2011 levels	301,524 233,226	£169,619,895 £131,132,464
	Predicted concentration between 2011 and 2030	154,011 **85,184**	£89,318,091 **£50,552,040**

For anthropogenic $PM_{2.5}$ assuming no net migration, with projected new births, 2011-2134, compared with life years lived with baseline mortality rates (incorporating mortality improvements over time) with a relative risk (RR) of 1.06 per 10 $\mu g\ m^{-3}$ of anthropogenic $PM_{2.5}$ without cut-off and with 7 $\mu g\ m^{-3}$ cut-off[19], with lags from the USEPA.
For NO_2 assuming no net migration, with projected new births, 2011-2134, compared with life years lived with baseline mortality rates (incorporating mortality improvements over time) with a relative risk (RR) of 1.023 per 10 $\mu g\ m^{-3}$ of NO_2 without cut-off and with 5 $\mu g\ m^{-3}$ cut-off, with lags from the USEPA.
(Results with cut-offs do not extrapolate beyond the original data, results with no cut-off represent the possibility that there are effects below the cut-off value (it is unknown whether or not this is the case).)
Figures in bold are the larger of the alternative estimates using $PM_{2.5}$ or NO_2, as summarised in the headline results. Note that the comparison for which is largest for the predicted concentration changes is across the results either without a cut-off (first row in each cell; 297,060 vs 154,011) or with a cut-off (second row in each cell; 85,184 vs 57,453) using Life year lost of predicted concentration between 2011 and 2030 results as an example.

[19]It is possible that this cut-off will be defined at a value lower than 7 $\mu g\ m^{-3}$ in the future as this is based on a 2002 study. The concentration-response function and its confidence intervals have been updated using a 2013 meta-analysis (the central estimate happened to remain the same). The cut-off has not so far been updated to reflect the range of the data in the meta-analysis.

Table 3 also gives the economic impacts (economic costs). Note that these are derived from applying monetary valuation to the health impacts. The monetary values are derived from surveys of what people are willing to pay to avoid the risk of the relevant health impact. They do not represent the costs of the policies or the costs to the NHS.

If 2011 concentrations of anthropogenic $PM_{2.5}$ remained unchanged for 124 years, the annualised economic cost would be around £100 – 230 million. This improves to around £30 – 170 million with the projected baseline concentration changes examined here.

If 2011 concentrations of NO_2 remained unchanged for 124 years, the annualised economic cost would be around £130 – 170 million. This improves to around £50 – 90 million with the predicted concentration between 2011 and 2030 changes examined here.

The **overall summary** for the projected baseline would be annualised economic costs of around **£50 to 170 million**.

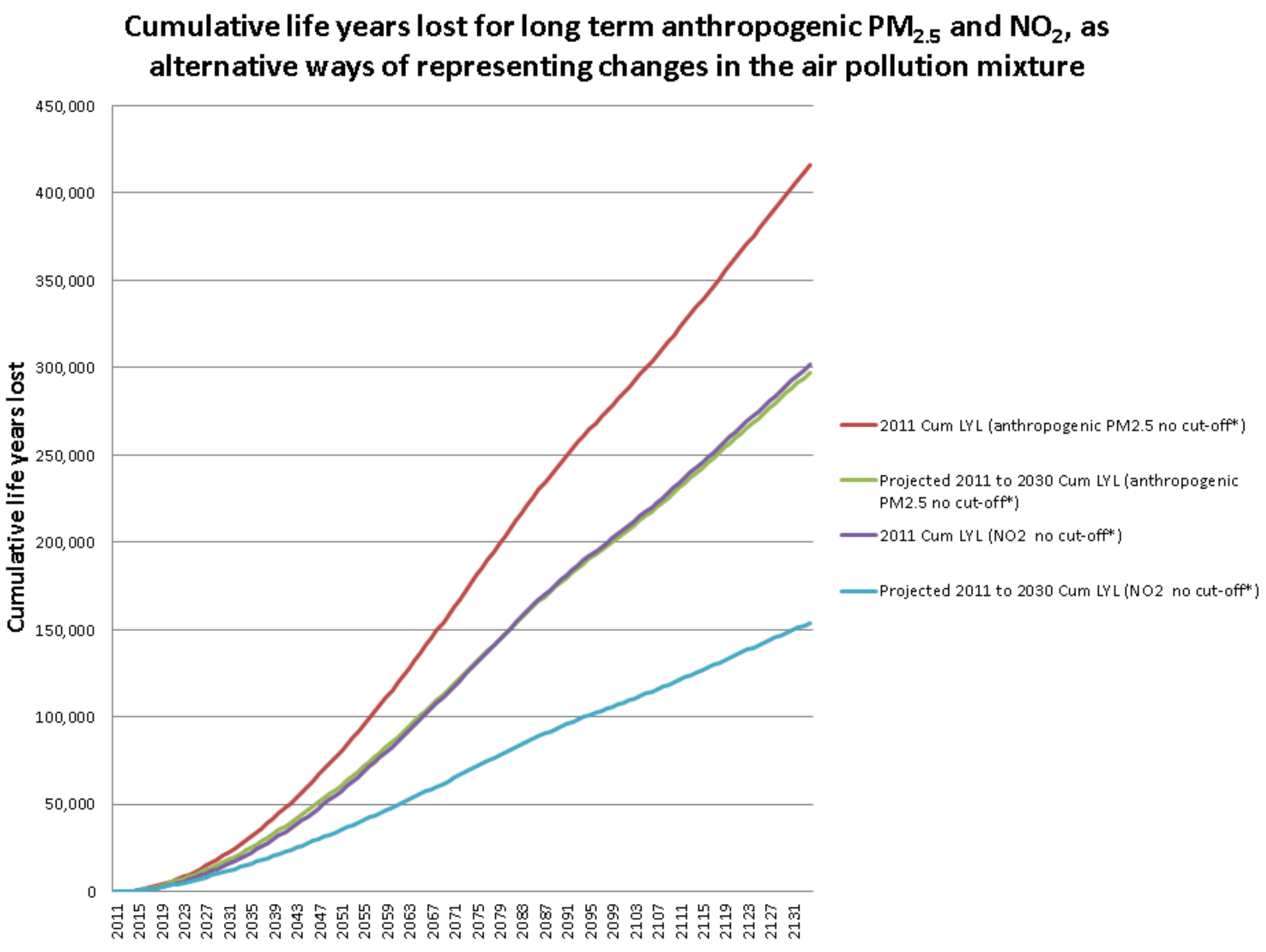

Figure 4 Cumulative life years lost for anthropogenic $PM_{2.5}$ and NO_2 if 2011 concentrations remained unchanged and the baseline (current policies 2011-2030) across Bristol population (no migration), with projected new births, compared with life years lived with baseline mortality rates (incorporating mortality improvements over time) 2011-2134. RR 1.06 per 10 μg m^{-3} for anthropogenic $PM_{2.5}$ and RR 1.023 per 10 μg m^{-3} for NO_2, EPA lag

* Cut-off results not shown

Figure 4 shows that the cumulative life years lost for the predicted concentration between 2011 and 2030 accumulates more slowly than the constant 2011 concentration results for both anthropogenic $PM_{2.5}$ and NO_2 as a result of the reduced concentrations from 2011 to 2030. It is worth remembering that there is a delay before the full benefits of concentration reductions are achieved. This is not just due to a lag between exposure and effect, but also because the greatest gains occur when mortality rates are highest i.e. in the elderly.

Table 4 shows the differences between the predicted concentrations between 2011 and 2030 and both particulate levels and NO_2 concentration constant at 2011 levels. Using $PM_{2.5}$ as an indicator of the regional pollution and some of the local pollution mixture gives an estimate of 120,000 life years gained as a result of the predicted concentration between 2011 and 2030. Using NO_2 as an indicator of mostly the local pollution mixture and the rural pollution gives a larger estimate of 150,000 life years gained, although the $PM_{2.5}$ concentration response function (see Table 13) is much stronger than for NO_2 (RR 1.06 per 10 $\mu g\ m^{-3}$ for anthropogenic $PM_{2.5}$ and RR 1.023 per 10 $\mu g\ m^{-3}$ for NO_2). This makes sense because the concentration projected (2011 to 2030) suggests more continuous declines in NO_2 concentrations (likely to be mostly due to the improvement in NO_X emissions of large parts of the road transport sector) than for $PM_{2.5}$, reflecting the fact that PM reduction from traffic is not larger due to the increasing contribution from non-exhaust emissions[20] and also that the declines in regional $PM_{2.5}$ are relatively small.

Thus, using NO_2 rather than $PM_{2.5}$, as the indicator of changes in the traffic pollution mixture seems more appropriate for future changes as presented here. This is a different indicator compared with the overall impact in terms of life years lost[21]. Regional pollution is a greater contributor to absolute total concentrations than to future changes so there is also some sense in $PM_{2.5}$ being the indicator in this case.

The **overall summary** would be that taking into account predicted air pollution concentration changes between 2011 and 2030, the population in Bristol would **gain around 150,000 life years** over a lifetime.

[20] Particle traps/DPF already reduced most PM exhaust emissions form Traffic

[21] This was not the case for the cut-off, where NO_2 rather than $PM_{2.5}$ gives the larger result. But this may be mostly to do with the value of the cut-off.

Table 4 Life years <u>saved</u> (and associated monetised benefits) across Bristol City population of the predicted concentration between 2011 and 2030 compared with 2011 anthropogenic $PM_{2.5}$ concentrations and NO_2 remaining unchanged

Pollutant	Scenario	Total life years **saved** compared with 2011 concentrations maintained (without cut-off with cut-off)	Monetised benefits compared with 2011 concentrations maintained (without cut-off with cut-off)
Anthropogenic $PM_{2.5}$ (representing the regional air pollution mixture and some of the local mixture)	Predicted concentration between 2011 and 2030	118,687 122,551	£65,302,091 £67,376,063
NO_2 (representing the local mixture and the rural air pollution mixture)	Predicted concentration between 2011 and 2030	**147,513** **148,042**	**£80,301,804** **£80,580,424**

Figures in bold are the larger of the alternative estimates using $PM_{2.5}$ or NO_2, as summarised in the headline results. Note that the comparison for which is largest for the predicted concentration changes is across the results either without a cut-off (first row in each cell; 147,513 vs 118,687) or with a cut-off (second row in each cell; 148,042 vs 122,551) using total life years saved compared with 2011 concentrations maintained results as an example.

Table 4 also provides an estimate of the economic impact as a result of the improvements in pollution from 2011 to 2030 versus 2011 pollution remaining unchanged. The <u>**annualised monetary benefit**</u> of anthropogenic $PM_{2.5}$ and NO_2 improvements has been estimated to be up to <u>**£80 million**</u> (at 2014 prices).

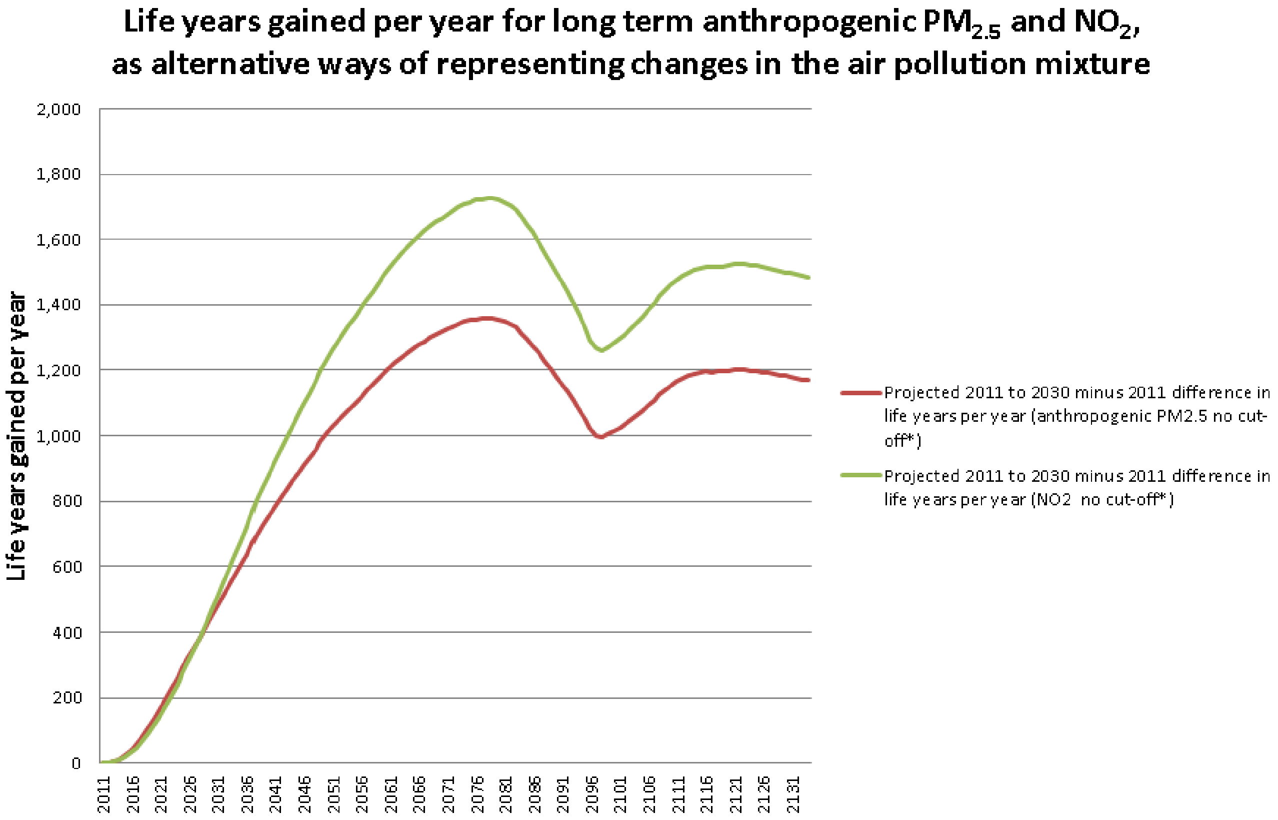

Figure 5 Life years gained per year from long-term exposure to the improvements in pollution from 2011 to 2030 of anthropogenic $PM_{2.5}$ and NO_2 relative to 2011 concentrations remaining unchanged

* Cut-off results not shown

Figure 5 shows the effect of the decrease in $PM_{2.5}$ and NO_2 concentration from 2011 to 2030 (as seen in Table 1 and Table 2).

5.2 Life-expectancy from birth in 2011

Total life years across the population is the most appropriate metric for cost-benefit analysis of policies as it captures effects in the entire population. However, it is a difficult type of metric to communicate as it is difficult to judge what is a 'small' answer or a 'large' answer. Life-expectancy from birth is a more familiar concept for the general public, although it only captures effects on those born on a particular date. Results for life expectancy from birth are shown in Table 5. Results for each constituency can be found in the Appendix in Table 23 and Table 24 (Loss of life expectancy for anthropogenic $PM_{2.5}$ and NO_2 with and without a cut-off).

This shows that the average loss of life expectancy from birth in Bristol would be about 16 – 36 weeks for males and 13 – 31 weeks for females if 2011 $PM_{2.5}$ concentrations were unchanged but improves to 5 – 25 weeks for males and 4 – 22 weeks for females for the predicted concentration changes between 2011 and 2030 (an improvement by about 9-11 weeks).
Using NO_2, the average loss of life expectancy from birth in birth would be about 20 – 26 weeks for males and 17 – 22 weeks for females if NO_2 concentrations were unchanged from 2011 but

improves by about 11-14 weeks to 7 – 13 weeks for males and 6 – 11 weeks for females with projected future changes between 2011 and 2030 included.

The **overall summary** would be that the projected future changes provide an improvement in average life expectancy from birth in 2011 of around 2 – 3 months (9 – 14 weeks) but an average loss of life expectancy from birth in 2011 of around 1.5 to 6 months (6 – 25 weeks) remains even with the reduced concentrations. Males are more affected than females – this is mainly due to the higher mortality rates in men compared with women rather than differences in air pollution exposure. The concentration-response function is implemented as a percentage change in baseline mortality rates. If the baseline mortality rates are higher then the absolute impact is higher even though the percentage change is the same.

Table 5 Loss of life expectancy by gender across Bristol City from birth in 2011 (followed for 105 years) for anthropogenic $PM_{2.5}$ and NO_2

Pollutant	Scenario	Loss of life expectancy from birth compared with baseline mortality rates, 2011 birth cohort (in weeks) (without cut-off with cut-off)	
		Male	Female
Anthropogenic $PM_{2.5}$	Concentration does not reduce from 2011 levels	36.0 15.6	30.9 13.4
	Predicted concentration between 2011 and 2030	**25.4** 4.6	**21.9** 3.9
NO_2	Concentration does not reduce from 2011 levels	26.1 20.2	22.3 17.2
	Predicted concentration between 2011 and 2030	12.6 **6.6**	10.8 **5.6**

Figures in bold are the larger of the alternative estimates using $PM_{2.5}$ or NO_2, as summarised in the headline results. Note that the comparison for which is largest for the predicted concentration changes is across the results either without a cut-off (first row in each cell; 25.4 vs 12.6) or with a cut-off (second row in each cell; 6.6 vs 4.6) using Male results as an example.

Additional data such as the loss of life expectancy lower and upper estimate and the full range of confidence intervals with and without the counterfactual for both $PM_{2.5}$ and NO_2 are available upon request to the authors.

6.0 Health Estimates of the mortality burden of air pollution

6.1 Burden background

Burden calculations are a snapshot of the burden in one year, assuming that concentrations had been the same for many years beforehand. They are intended as a simpler calculation than the more detailed assessments that are given above (in the mortality impact section). They are not suitable for calculation is several successive years as they do not have a mechanism for allowing the number of deaths the year before to influence the age and population size the following year as the lifetables used in impact calculations do. They are included here as a comparison with similar calculations presented elsewhere (COMEAP, 2010; Walton et al., 2015; Dajnak et al., 2018; Dajnak et al., 2019). The concentration-response functions used for these calculations are evolving over time. Previous recommendations favoured methods similar to the single pollutant model approach presented below. The latest COMEAP (2018a) report shows that a majority of the committee supported a new approach using information from multi pollutant model results but COMEAP (2018a) also recommended using a range to reflect the uncertainty. Single pollutant models relate health effects to just one pollutant at a time, although because pollutants tend to vary together, they may in fact represent the effects of more than one pollutant. Single pollutant models for different pollutants cannot therefore be added together as there may be substantial overlap. Multi-pollutant models aim to disentangle the effects of separate pollutants but this is difficult to do. Despite the best attempts, it may still be the case that some of the effect of one pollutant 'attaches' to the effects ascribed to another pollutant, leading to an underestimation of the effects of one pollutant and an overestimation of the effects of another. In this situation, the combined effect across the two pollutants should give a more reliable answer[22] than the answers for the individual pollutants that may be over- or under-estimated. This was the basis for the approach described below, including adding results derived from information within each of 4 separate studies first, before combining them as a range. The intention is not to present the individual pollutant results separately as final results, although the calculations for individual pollutants are done as intermediate stages towards the overall results.

[Burden calculations would normally include accompanying estimates of the burden of life years lost[23]. This would require inputting average loss of life expectancy by age and gender for calculations in each ward. For this small project, it was not possible to do this.]

The calculations are based on deaths from all causes including respiratory, lung cancer and cardiovascular deaths, the outcomes for which there is strongest evidence for an effect of air pollution.

6.2 Combined estimate for $PM_{2.5}$ and NO_2 using multi pollutant model results

Using the exploratory new combined method (COMEAP, 2018a) gives an estimate for the 2011 mortality burden in Bristol of 2011 levels of air pollution (represented by anthropogenic $PM_{2.5}$ and

[22]This is certainly true for estimates based on the interquartile range within an individual study. However, application to situations where the ratio between the interquartile ranges for the two pollutants differs from that in the original study may exaggerate the contribution of one pollutant over another. The views of COMEAP members differed on how important this issue might be in practice, with the majority considering that a recommended approach on the basis of combined multi-pollutant model estimates could still be made provided caveats were given.

[23]Burden life years lost represent a snapshot of the burden in one year and are not to be confused with the full calculation of the life years lost for the health impact of air pollution concentration changes over time as presented in the next section.

NO_2) to be equivalent to 200 to 260 attributable deaths at typical ages, or a result equivalent to 130 to 140 deaths when cut-offs for each pollutant were implemented. Estimates for individual constituencies are provided in Table 6. The results varied by constituency with the highest in Bristol North West and the lowest in Bristol West. The ranking by constituency in Table 6 did not follow the ranking in pollutant concentrations (see Table 1 and Table 2). This is because the results are also influenced by variations in death rates by constituency (highest in Bristol North West, lowest in Bristol West), which in turn are driven in part by the proportion of elderly in the population (highest in Bristol North West, lowest in Bristol West) and the level of deprivation (highest in Bristol South, lowest in Bristol North West and Bristol West). Details are given in Table 26 in the Appendix. Note that the level of deprivation by constituency does not represent the complexity and spatial variability within a constituency as can be seen in section 7.1 (Figure 6).

These results use recommendations from COMEAP, 2018a. For each of the four individual cohort studies that included multi-pollutant model results[24], the burden results were estimated separately using mutually adjusted summary coefficients for $PM_{2.5}$ and NO_2 and then the adjusted $PM_{2.5}$ and NO_2 results were summed to give an estimated burden of the air pollution mixture. Example of the calculations for each study for individual constituency and Bristol of 2011 levels of NO_2 and $PM_{2.5}$ can be found in the appendix in Table 27 and Table 28. The uncertainty of each separate study was not quantified (COMEAP, 2018a) but it is worth noting that each of the individual results also has uncertainty associated with it.

Table 6 Estimated burden (from the estimates derived by using information from multi-pollutant model results from 4 different cohort studies) of effects on annual mortality in 2011 of 2011 levels of anthropogenic $PM_{2.5}$ and NO_2 (with and without cut-off)

Zone	Anthropogenic $PM_{2.5}$ and NO2 (without cut-off)	Anthropogenic $PM_{2.5}$ and NO2 (with cut-off)
	Attributable deaths (using coefficients derived from information in 4 studies below*)	Attributable deaths (using coefficients derived from information in 4 studies below*)
Bristol East	47 - 61	30 - 32
Bristol North West	64 - 82	41 - 45
Bristol South	51 - 70	31 - 34
Bristol West	38 - 47	27 - 29
Bristol City	200 - 261	129 - 140

*Using COMEAP's recommended concentration-response coefficient of 1.029, 1.033, 1.053 and 1.019 per 10 µg m^{-3} of anthropogenic $PM_{2.5}$ derived by applying to a single pollutant model summary estimate the % reduction in the coefficient on adjustment for nitrogen dioxide from the Jerrett *et al* (2013), Fischer *et al* (2015), Beelen *et al* (2014) and Crouse *et al* (2015) studies , respectively

*Using COMEAP's recommended concentration-response coefficient of 1.019, 1.016, 1.011 and 1.020 per 10 µg m^{-3} of NO_2 derived by applying to a single pollutant model summary estimate the % reduction in the coefficient on adjustment for $PM_{2.5}$ from the Jerrett *et al* (2013), Fischer *et al* (2015), Beelen *et al* (2014) and Crouse *et al* (2015) studies , respectively

6.3 Single pollutant model estimates

The previous mortality burden method using single pollutant model estimates would have estimated that Bristol's 2011 levels of anthropogenic $PM_{2.5}$ would lead to effects equivalent to 210

[24] Some further cohort studies were omitted because of high correlations between pollutants (see COMEAP (2018a)

(range[25] 140 to 280) attributable deaths at typical ages, or results equivalent to 90 (range 60 to 120) deaths when the cut-off was implemented. Estimates for individual constituencies are provided in Table 7. This represents the regional pollution mixture and partially represents the contribution from traffic pollution.

These results use recommendations from COMEAP, 2010. Walton et al. (2015) used both COMEAP (2010) recommendations and WHO (2013) recommendations that included recommendations for nitrogen dioxide to provide estimates for London. The results were presented as a range from $PM_{2.5}$ alone to the sum of the $PM_{2.5}$ and NO_2 results, but the uncertainty of the latter was emphasized. Since then it has become clearer that the overlap is likely to be substantial (COMEAP, 2015). COMEAP (2018a) concluded that the combined adjusted coefficients were similar to, or slightly larger than, the single-pollutant association reported with either pollutant alone.

The lower and upper estimates in Table 7 are based on the 95% confidence intervals (1.04 – 1.08) around the pooled summary estimate (1.06) for the increase in risk from Hoek et al (2013). COMEAP recently agreed to use this range (COMEAP, 2018b) rather than the wider ones of 1.01 – 1.12 in the original COMEAP (2010) report. Nonetheless, the wider ones remain reflective of the fact that the uncertainties are wider than just the statistical uncertainty represented by the confidence intervals. We have included results for this wider range of uncertainty in Table 25 of the Appendix but as a rough guide the range goes from around a sixth to around double the central estimate in Table 7.

Table 7 Estimated burden (from single-pollutant model summary estimate) of effects on annual mortality in 2011 of 2011 levels of anthropogenic $PM_{2.5}$ (with and without cut-off)

Zone	Anthropogenic $PM_{2.5}$ (without cut-off)			Anthropogenic $PM_{2.5}$ (with cut-off)		
	Attributable deaths			Attributable deaths		
	Central estimate	Lower estimate	Upper estimate	Central estimate	Lower estimate	Upper estimate
Bristol East	50	34	65	22	15	28
Bristol North West	66	45	87	28	19	37
Bristol South	59	40	77	23	16	31
Bristol West	36	25	47	17	12	23
Bristol City	211	144	276	90	61	119

Using COMEAP's recommended concentration-response coefficient of 1.06 per 10 µg m^{-3} of anthropogenic $PM_{2.5}$ for the central estimate (lower estimate RR of 1.04 and upper estimate RR 1.08)

In addition to the combined multi-pollutant model derived estimates in the section above, the COMEAP (2018a) report suggests also calculating the burden using the single pollutant model result for NO_2 (this may represent the burden of traffic pollution more clearly than that of $PM_{2.5}$). The results give estimates that Bristol's 2011 levels of NO_2 lead to effects equivalent to 150 (range[26] 50 to 240) attributable deaths at typical ages, or results equivalent to 110 (range 40 to 180) deaths when the cut-off was implemented. Estimates for individual constituencies are provided in Table 8.

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[25] From the 95% confidence interval around the coefficient.
[26] From the 95% confidence interval around the coefficient.

Table 8 Estimated burden (from single pollutant model summary estimate) of effects on annual mortality in 2011 of 2011 levels of NO_2 (with and without cut-off)

Zone	NO_2 (without cut-off) Attributable deaths			NO_2 (with cut-off) Attributable deaths		
	Central estimate	Lower estimate	Upper estimate	Central estimate	Lower estimate	Upper estimate
Bristol East	34	12	54	26	9	41
Bristol North West	48	17	76	37	13	58
Bristol South	37	13	58	27	9	42
Bristol West	30	11	47	25	9	39
Bristol City	149	53	235	114	40	180

Using COMEAP's recommended concentration-response coefficient of 1.023 per 10 µg m^{-3} of NO_2 for the central estimate (lower estimate RR of 1.008 and upper estimate RR 1.037)

6.4 Summary of burden results

Results without the cut-off give a range of 200-260 attributable deaths using the approach derived from multi-pollutant model results. This compares with around 210 attributable deaths[27] using the single-pollutant model estimate for $PM_{2.5}$ (the previous method) and around 150 attributable deaths using the single-pollutant model estimate for NO_2 (a good indicator of traffic pollution). As expected, the estimate combining effects of NO_2 and $PM_{2.5}$ is slightly larger than for either pollutant alone but not by much, reflecting the substantial overlap between the single pollutant model estimates for $PM_{2.5}$ and NO_2. Nonetheless, there are substantial ranges of uncertainty around these estimates so it is not clear cut that there is an additional effect over and above estimates using the previous method.

The message from the results with a cut-off is similar with a range of 130-140 attributable deaths using the approach derived from multi-pollutant model results compared with 90 ($PM_{2.5}$ single-pollutant model) and 110 (NO_2 single-pollutant model). In this case, the result for NO_2 is larger than that for $PM_{2.5}$ - probably a reflection of the different cut-offs for NO_2 and $PM_{2.5}$.

In developing policy in the face of uncertainty, it is useful to have guidance on the result using the most conservative assumptions and that using approaches using recent trends in evidence and methods that may also be more uncertain. In this case, the 'conservative assumptions' result would be 90 attributable deaths (long-established method for $PM_{2.5}$, avoids the complexities of interpreting multi-pollutant model results) and the 'exploratory, more up to date, extrapolate beyond the data' results would be 200-260 attributable deaths (combined NO_2 and $PM_{2.5}$; no cut-off). For messages incorporating most of the uncertainties, the message would be 'somewhere between about 50 and 260 attributable deaths'.

[27]More fully 'results equivalent to xx attributable deaths at typical ages'.

7.0 Discussion

This study addressed the effect of air pollution on deaths and loss of life-expectancy. This included all causes of death grouped together so covers, for example, respiratory, lung cancer and cardiovascular deaths for which there is good evidence for an effect of air pollution. It does not, however, cover the effect of air pollution on health where this does not result in death. So well established effects (such as respiratory and cardiovascular hospital admissions, effects on asthma, low birth weight etc) and other outcomes more recently potentially linked with air pollution (such as dementia) are not included. Their inclusion would increase the benefit of policies to further reduce air pollution.

7.1 Impact of Air Pollution on inequalities, ethnic groups, population change, migration and students within Bristol

The HIA results' variation and ranking by constituency did not follow the ranking in pollutant concentrations. As already discussed in section 6.2, this is because the results are also influenced by variations in death rates, the proportion of elderly in the population and the level of deprivation by constituency as seen in Table 26 in the Appendix.
Individuals of lower social classes may experience increased susceptibility to the negative air pollution-related health effects particularly in urban areas, where they are possibly more affected than individuals of higher social class (discussed in Williams et al., 2018b). As a result, higher levels of pollution exposure and socioeconomic deprivation may lead to impaired health.

Some indicators in Table 9 such as income and employment show that Bristol have more income- and employment-deprived people than some English core[28] cities like Newcastle and Nottingham. But overall, Bristol continues to be one of the relatively less deprived English cities according to most measures in Table 9 such as indices of multiple deprivation (IMD) or proportion of LSOAs (Lower Layer Super Output Area) in the most deprived 10% nationally. Nonetheless, Bristol has deprivation 'hot spots' that are amongst some of the most deprived in the country as identified in Figure 6.

On the whole, the Bristol map of multiple deprivation (Figure 6) alongside $PM_{2.5}$ and NO_2 air pollution maps (Figure 2 and Figure 3) does not particularly show environmental inequality (in which socioeconomically disadvantaged populations are among the most exposed). An exception is the area of Lawrence Hill (see wards boundaries in Figure 1) identified as having both some of the highest levels of deprivation and air pollution in Bristol. Furthermore, areas (LSOAs) around and within Lawrence Hill have the highest Black and Minority Ethnic (BME) population in strong contrast with the rest of in Bristol (Figure 7).

Bristol's maps of (i) population change between 2007 and 2017 (Figure 8), (ii) new migrants arriving in UK since 2001 (Figure 9) and (iii) full time students living in Bristol during term time (Figure 10) show that the areas of (i) exceptional population growth (70% population change in Central, 55% in Hotwells & Harbourside and 39% in Lawrence Hill wards), (ii) the areas where most recent migrants tend to live (in inner city areas of Bristol in particular in Central and Lawrence Hill wards and some part of Hotwells & Harboursidse) and (iii) the areas where most students live during term time (including Central, Cotham, Clifton Down, Hotwells and Harbourside and Clifton

[28] https://www.corecities.com/

wards) are concentrated in zones of the city linked to the highest concentrations of $PM_{2.5}$ and NO_2 air pollution as can be seen in Figure 2 and Figure 3 maps.

In recognition of the World Health Organization's advocacy that there is no safe limit for exposure to air pollution, all Bristol citizens would benefit greatly from a reduction in air pollution concentrations, ultimately to achieve the lowest possible levels of pollution.

Table 9 English Core City Local Authority level Summaries including Indices of Multiple Deprivation (IMD)[29] 2015: Local Authority Rankings[30]
(1 = most deprived and 326 is least deprived of the English local authority areas)

Core City	Average rank		Average score		Proportion of LSOAs in most deprived 10% nationally		IMD - Extent		Local concentration	Income - Scale		Employment - Scale	
	average rank	rank/326	average score	rank	%	rank/326	%	rank/326	rank/326	number	rank/326	number	rank/326
Bristol	**19,760**	**77**	**27.2**	**62**	**16%**	**55**	**29%**	**67**	**32**	**72,003**	**11**	**35,777**	**9**
Birmingham	24,955	11	37.8	7	40%	6	56%	6	21	262,497	1	114,273	1
Leeds	18,462	100	26.6	70	22%	31	31%	58	24	120,622	3	59,553	3
Liverpool	25,461	7	41.1	4	45%	4	59%	2	7	119,589	4	61,962	2
Manchester	26,367	1	40.5	5	41%	5	59%	1	11	123,532	2	57,127	4
Newcastle	18,993	92	28.3	53	22%	30	35%	45	13	54,583	31	26,806	23
Nottingham	25,061	10	36.9	8	34%	8	56%	7	26	69,166	12	33,532	10
Sheffield	18,944	94	27.6	60	23%	26	34%	47	29	95,998	6	46,227	7

[29] Note that IMD has seven thematic domains: income deprivation, employment deprivation, education skills and training deprivation, health deprivation and disability, crime, barriers to housing and services and living environment deprivation(LED). LEV falls into two sub-domains: indoor environment and outdoor environment containing measures of air quality and road traffic accidents.
[30] https://www.bristol.gov.uk/documents/20182/32951/Deprivation+in+Bristol+2015

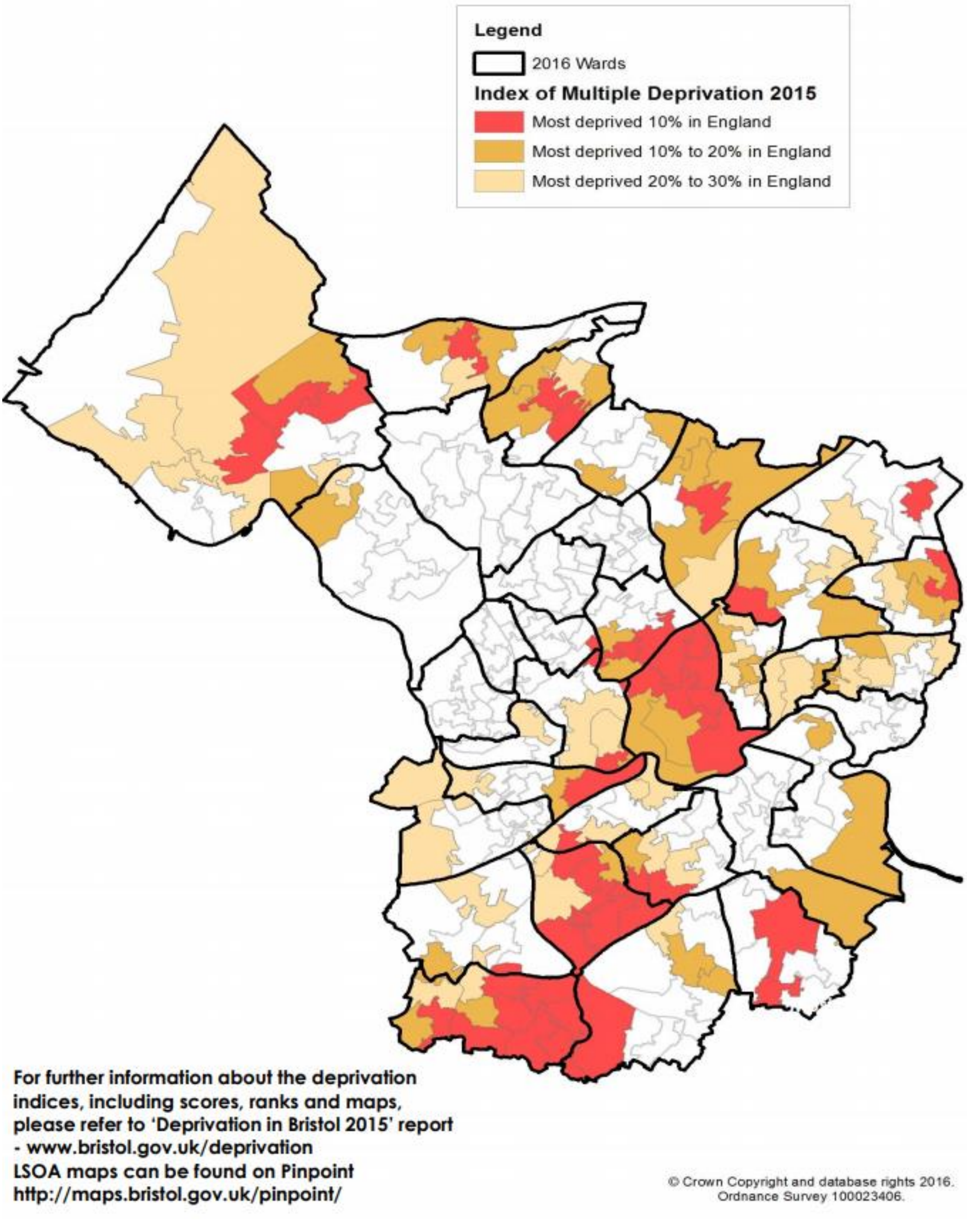

Figure 6 Map of Index of Multiple Deprivation 2015 in Bristol[31]
Source: DCLG English Indices of Deprivation 2015

[31] https://www.bristol.gov.uk/documents/20182/436737/Hartcliffe+and+Withywood.pdf/49d31847-00da-471c-95c8-82630662e073

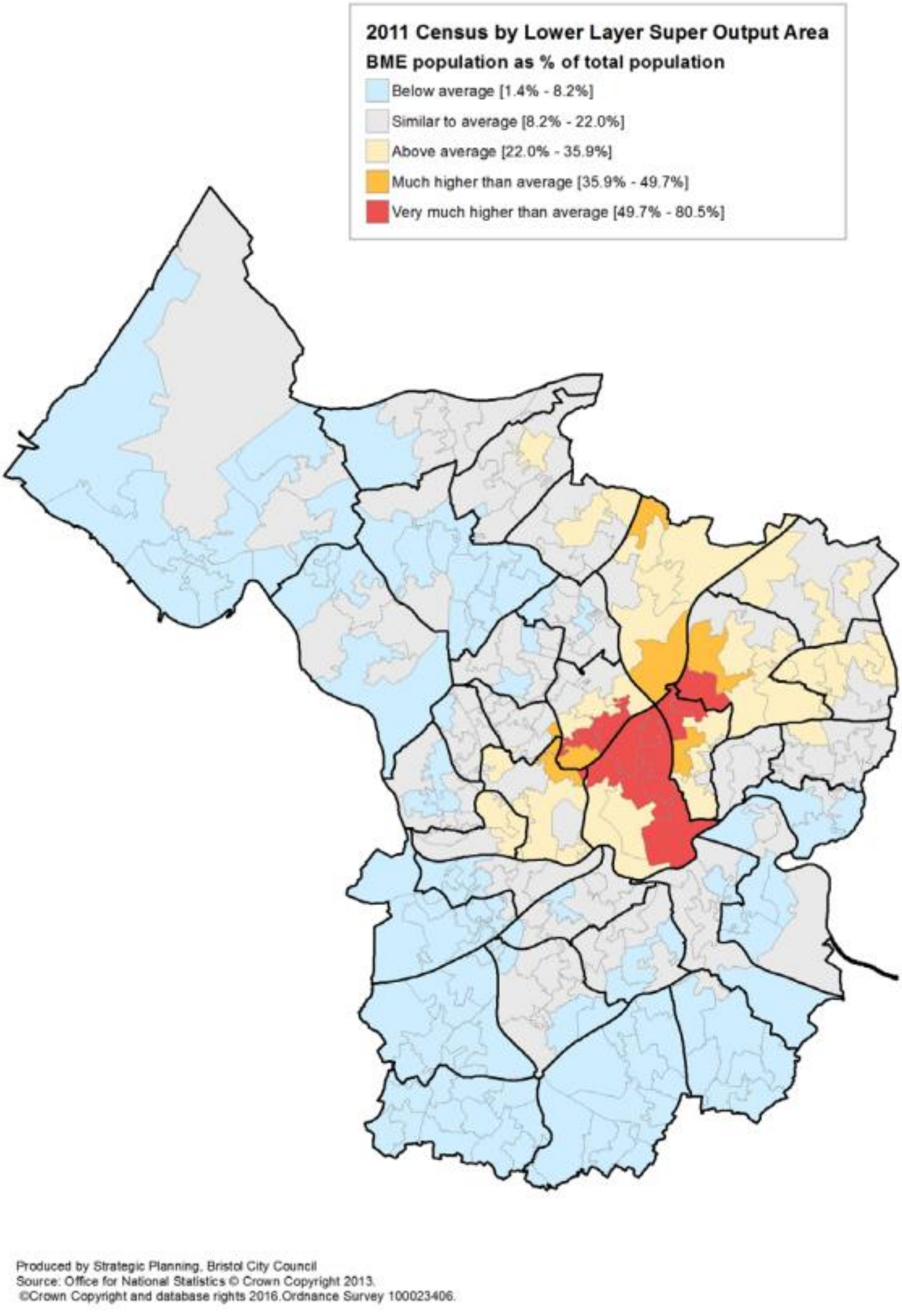

Figure 7 Map of 2011 Black and Minority Ethnic (BME) population as % of total population by LSOA (Lower Layer Super Output Area) in Bristol[32]
Source: 2011 Census Office for National Statistics © Crown Copyright 2013 [from Nomis]

32 https://www.bristol.gov.uk/documents/20182/33904/Population+of+Bristol+August+2019.pdf/96d16ba4-49f6-c535-ba7d-a11f24b8d3b3

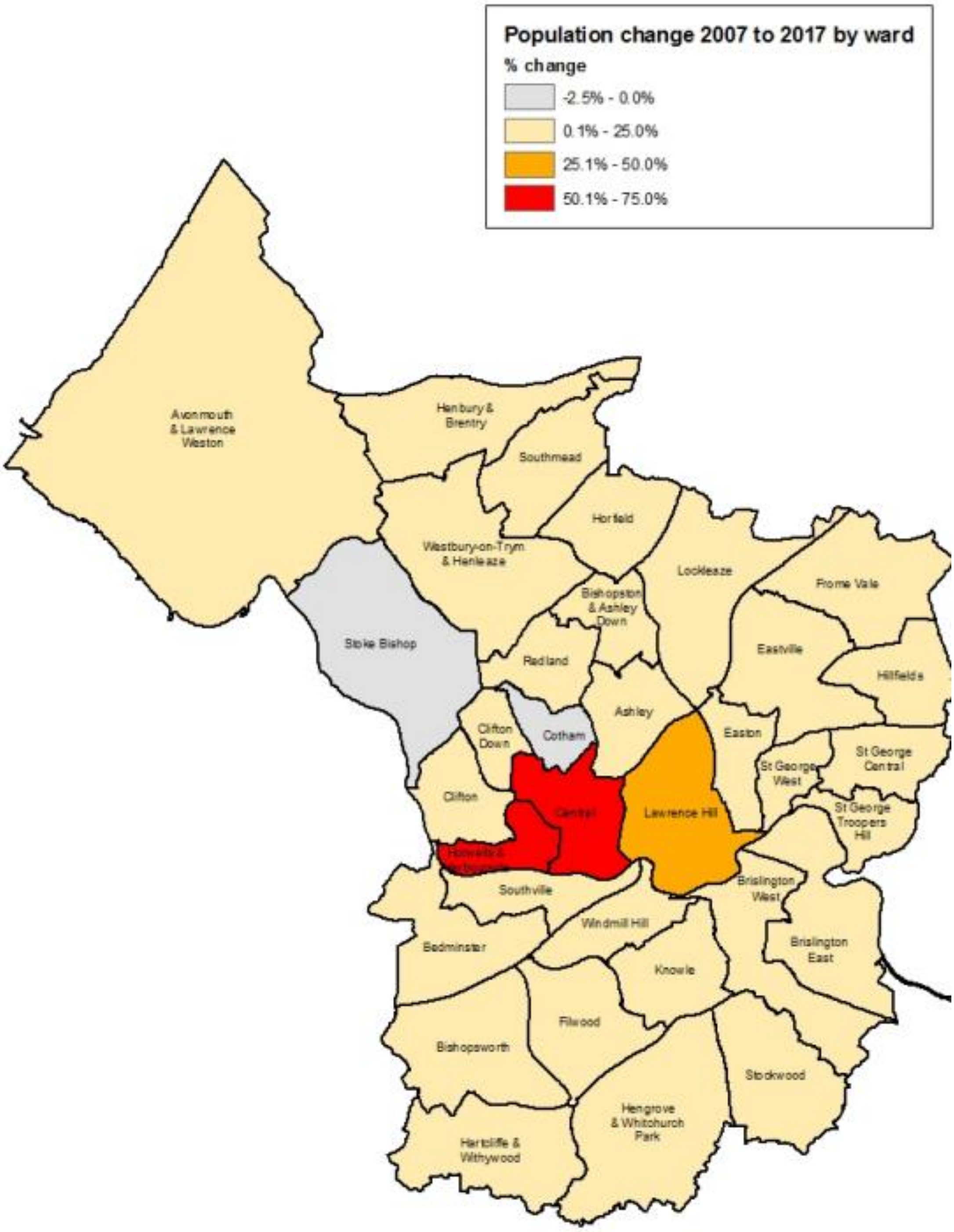

Figure 8 Map of population change between 2007 and 2017 by wards in Bristol[33]
Source: Annual Small Area Population Estimates, Office for National Statistics © Crown Copyright 2018

33 https://www.bristol.gov.uk/documents/20182/33904/Population+of+Bristol+August+2019.pdf/96d16ba4-49f6-c535-ba7d-a11f24b8d3b3

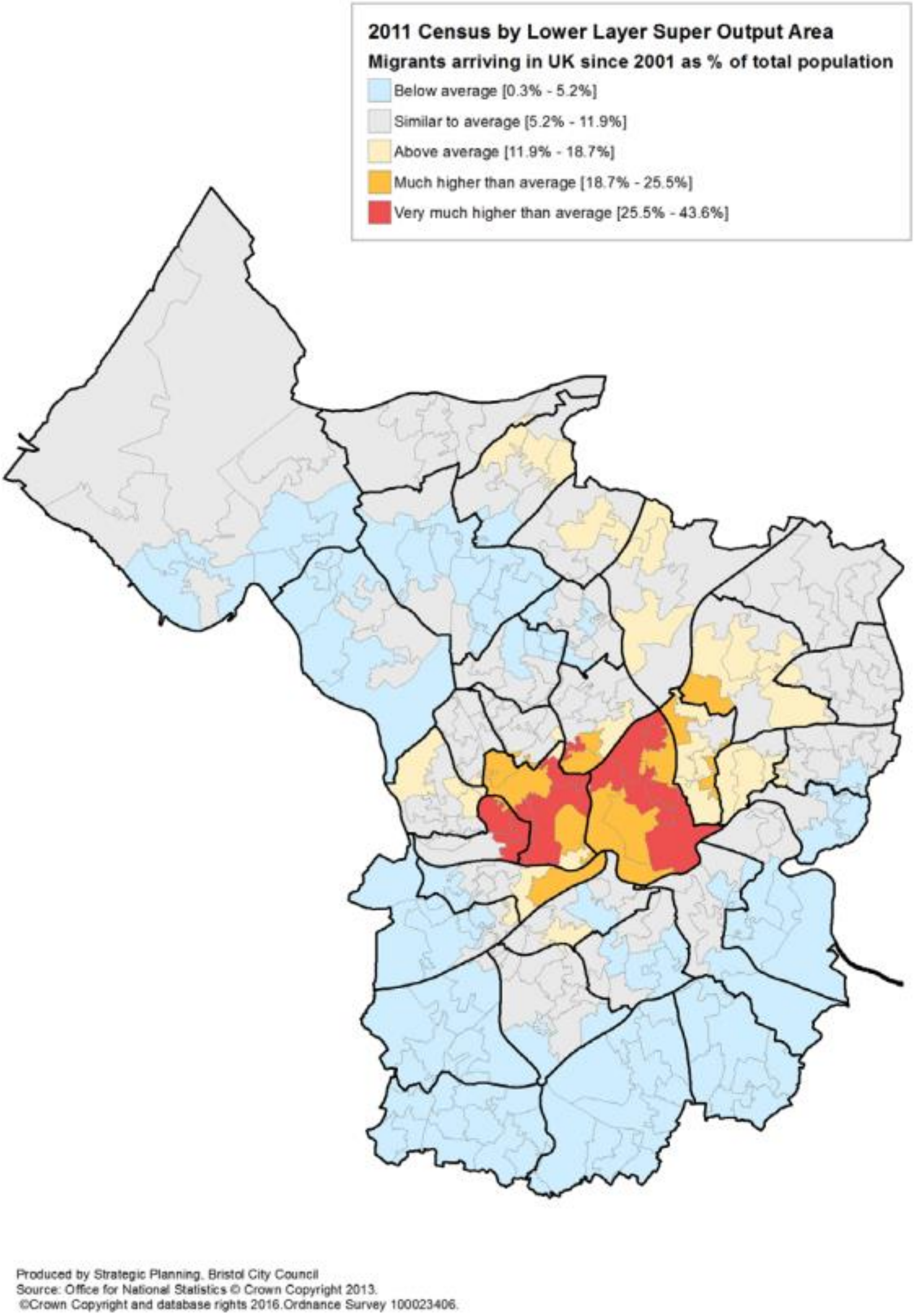

Figure 9 Map of new migrants arriving in UK since 2001 as % of total population (2011 census by LSOA)[34]

Source: 2011 Census Office for National Statistics © Crown Copyright 2013 [from Nomis]

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[34] https://www.bristol.gov.uk/documents/20182/33904/Population+of+Bristol+August+2019.pdf/96d16ba4-49f6-c535-ba7d-a11f24b8d3b3

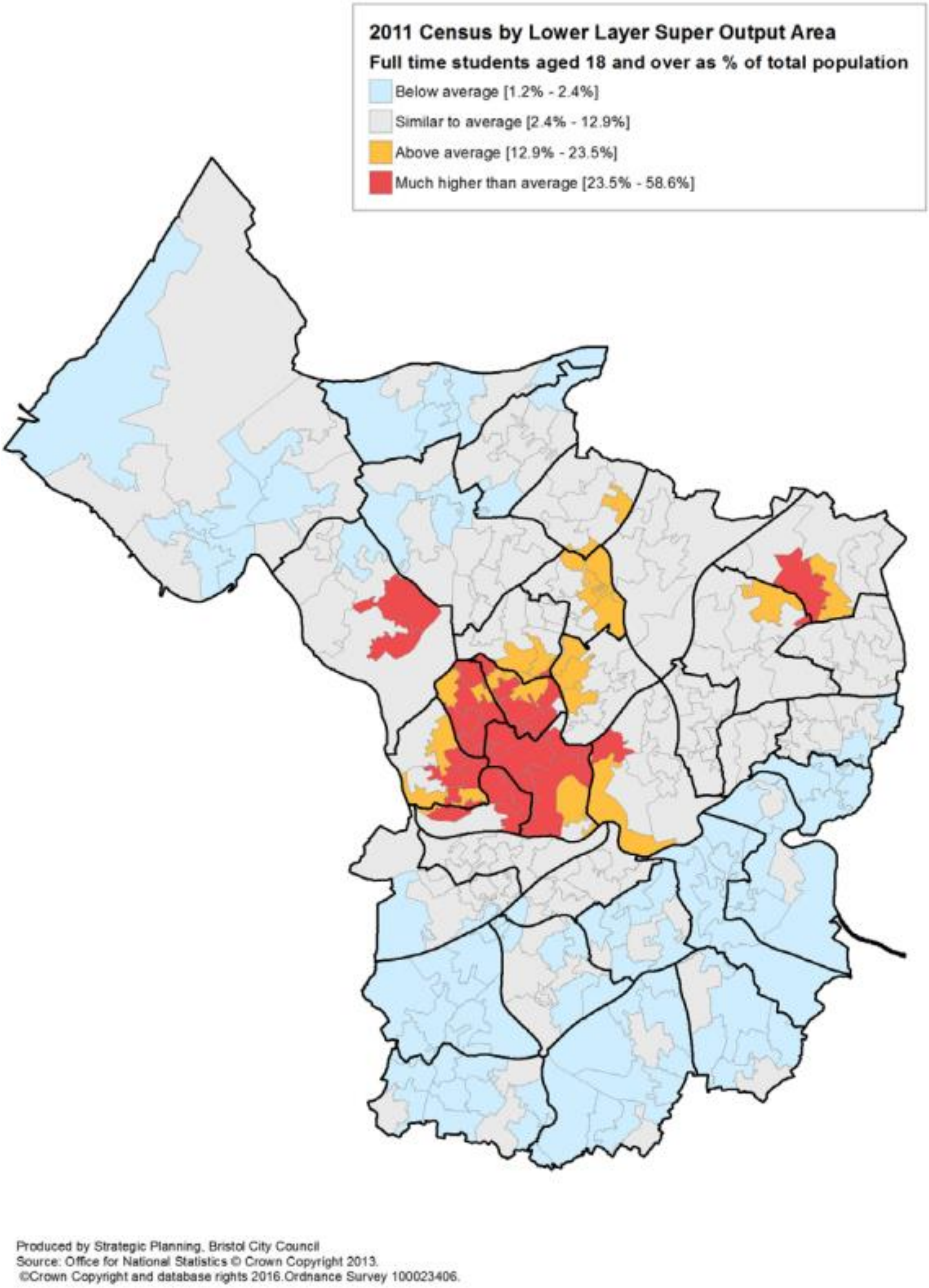

Figure 10 Map of full time students aged 18 and over living in Bristol during term time as % of total population (2011 census by LSOA)[35]
Source: 2011 Census Office for National Statistics © Crown Copyright 2013 [from Nomis]

[35] https://www.bristol.gov.uk/documents/20182/33904/Population+of+Bristol+August+2019.pdf/96d16ba4-49f6-c535-ba7d-a11f24b8d3b3

7.2 Comparison with results for Greater Manchester (GM), Birmingham City, Liverpool City Region (LCR) and London

The current authors performed a similar analysis for Greater Manchester (Dajnak et al., 2018), for Birmingham (Dajnak et al., 2019) and more recently for Liverpool City Region (in press). This analysis was similar to the one for Greater Manchester, Birmingham City and Liverpool City Region for the impact calculations although the Greater Manchester report predated the multi-pollutant model aspects of the new burden methodology published in COMEAP (2018). Even with the same methodology, comparisons for the impact calculations are complex because the results are driven by multiple factors changing over time (not only the pollutant concentrations but also the mortality rates, new births and the changes in population age distribution and size as a result of the pollutant changes). Nonetheless, some approximate comparisons can be made.

Life years lost still remaining after pollution improvements: The largest result in Bristol, Greater Manchester, Liverpool City Region and Birmingham City was for $PM_{2.5}$ with no cut-off. The result was lowest for Bristol (0.3 million life years lost) when compared with Greater Manchester (1.6 million life years lost) and, Liverpool City Region and Birmingham city (both 0.8 million life years lost). The primary driver of this difference is probably the difference in population – Bristol is the largest city in the South West of England but is a smaller area (Table 12) and has the smallest population (<0.5 million) when compared with the population for Greater Manchester (2.7 million), Liverpool City Region (1.5 million) and Birmingham city at 1 million. Furthermore, the Bristol death rate (Table 12) is also the lowest between the four cities/region of interest (in these studies) which will result in lower life years lost relative to Greater Manchester, LVR and Birmingham city.
The equivalent result for NO_2 with no cut-off is 150,000 life years lost in Bristol, again the lowest of the four cities/region of interest with the explanations being similar, 1 million life years lost in Greater Manchester and 0.5 million life years lost in both Liverpool City Region and Birmingham city.
In addition, Bristol has lower NO_2 concentrations than GM and Birmingham and lower $PM_{2.5}$ concentrations than Birmingham (Table 11), further explaining the lower results in comparison with these cities. On the other hand, Bristol does have higher NO_2 concentrations than LCR and higher $PM_{2.5}$ concentrations than LCR and GM but not to a sufficient extent to counteract the influence of its lower population and death rate i.e. the results are still lower overall despite the higher pollution concentrations in some cases.

The comparison of the results with a cut-off give different messages for NO_2 and $PM_{2.5}$. The comparison for NO_2 with a cut-off is similar to the no cut-off results (the result for Bristol is the lowest with 85,000 life years lost while Liverpool City Region and Birmingham, circa 300,000 life years lost, and Manchester, 560,000 life years lost). For $PM_{2.5}$, however, while the result for Bristol (60,000 life years lost) was substantially smaller than for Birmingham City (210,000 life years lost) (as expected from the smaller population) this was not as obvious for the comparisons against the other cities. The result for Bristol is similar to that for the Liverpool City Region (both around 60,000 life years lost), and smaller than Greater Manchester (175,000 life years lost) but by a smaller margin than expected for the difference in population. This is because the $PM_{2.5}$ concentrations in the LCR and GM are much lower in some areas than the 7 $\mu g\ m^{-3}$ cut-off. It is therefore assumed that the particulate pollution has no effect on life-years lost in those areas, reducing the total overall. (Strictly, the definition of a cut-off means it is unknown whether or not there are effects. In addition, this cut-off is based on Pope *et al* (2002) which in turn used particulate concentrations from many years earlier. As concentrations reduce and newer studies are completed, it is often found that the health effects at lower concentrations become clearer as there are more data points available for analysis at these lower concentrations.)

Table 10 Total life years lost across Bristol, the Liverpool City Region, Birmingham City and Greater Manchester population for anthropogenic $PM_{2.5}$ and NO_2 and the associated annualised economic impact (central estimate)

Pollutant	Scenario	Location	Life years lost Central estimate (without cut-off with cut-off)	Annualised economic impact (in 2014 prices) (without cut-off with cut-off)
Anthropogenic $PM_{2.5}$	Predicted concentration between 2011 and 2030	Bristol	**297,060** 57,453	**£168,836,821** £33,905,354
		Liverpool City Region	**798,521** 61,107	**£477,603,949** £40,773,443
		Birmingham City	**831,708** 213,344	**£467,766,599** £121,993,163
		Greater Manchester	**1,638,043** 175,471	**£954,495,447** £109,582,547
NO_2	Predicted concentration between 2011 and 2030	Bristol	154,011 **85,184**	£89,318,091 **£50,552,040**
		Liverpool City Region	493,408 **272,258**	£300,081,973 **£169,191,136**
		Birmingham City	505,434 **328,491**	£289,339,663 **£190,370,755**
		Greater Manchester	981,519 **561,169**	£586,562,264 **£343,719,554**

Table 11 Anthropogenic $PM_{2.5}$ PWAC (in µg m^{-3}) (annual) and NO_2 PWAC (in µg m^{-3}) (annual) for Bristol, Liverpool City Region (LCR), Birmingham City and Greater Manchester (GM)

Pollutant	Location	2011	2015 for Birmingham/GM 2017 for Bristol/LCR	2020	2025	2030
Anthropogenic $PM_{2.5}$ PWAC*	Bristol	11.81	9.18	8.77	8.33	8.30
	Liverpool City Region	10.39	7.52	7.21	6.93	6.89
	Birmingham City	12.82	9.81	9.21	9.02	8.99
	Greater Manchester	11.39	8.09	7.62	7.47	7.44
NO_2 PWAC*	Bristol	21.73	16.15	14.29	11.85	10.46
	Liverpool City Region	18.97	15.11	13.38	11.31	10.22
	Birmingham City	26.12	21.33	17.68	14.75	13.14
	Greater Manchester	22.39	18.78	14.94	12.08	10.65

*For Bristol: average of the PWAC by constituency from Table 1 and Table 2, above (see Dajnak et al., 2019 for Birmingham City). For Greater Manchester (Dajnak et al., 2018) and Liverpool City Region (in press), average of the PWAC by local authority from Table 1 and Table 2.

Table 12 Total population in 2011 and mortality rate (total death age 30 plus divided by total population age 30 plus) in Bristol, Liverpool City Region, Birmingham City and Greater Manchester

Location	Total population	Mortality rate (age group 30 plus)
Bristol	428,254	1.28%
Liverpool City Region	1,507,032	1.49%
Birmingham City	1,073,188	1.33%
Greater Manchester	2,682,727	1.36%

Loss of life expectancy still remaining after pollution improvements: The influence of the difference in pollution concentrations and death rate between Bristol, Liverpool City Region, Birmingham City and Greater Manchester can be seen more clearly in the results for loss of life expectancy from birth. This is because it comes from the total life years lost in those exposed for a lifetime divided by the size of that population. So, the difference in population has already been taken into account. The loss of life expectancy using $PM_{2.5}$ as an indicator without a cut-off was 22/25 weeks (Female/Male) in Bristol, 19/22 weeks (Female/Male) in Liverpool City Region, 21/24 weeks (Female/Male) in Greater Manchester and 25/29 weeks (F/M) in Birmingham City, similar to but not exactly following the $PM_{2.5}$ concentrations ranking order (Table 11). The comparison was similarly close for life expectancy using NO_2 without a cut-off as an indicator (11 – 13 weeks (Bristol) compared with 12 – 13 weeks (LCR), 12 – 14 weeks (GM) and 15-17 weeks in Birmingham). As with the previous discussions of total life years lost, the difference between Bristol, Liverpool City Region, Greater Manchester and Birmingham City is more marked for $PM_{2.5}$ with a cut-off than for NO_2 with a cut-off because the cut-off of 7 µg m^{-3} is closer to the general $PM_{2.5}$ concentrations.

Gains in life years from pollution improvements: Similar factors influence the comparative results for life years gained between the four cities, driven mainly by the population size, the pollution levels and by the NO_2 and $PM_{2.5}$ reductions in all four cities (Table 11), which also influence the answer. For example, the gains from $PM_{2.5}$ and NO_2 reductions in Bristol are a bit less than half and a third those in LCR, respectively.

Mortality burden: The mortality burden in Bristol (200-260 and 210 attributable deaths from multi-pollutant and single-pollutant model results, respectively) is smaller than for the Liverpool City Region (800-1,040 and 840 attributable deaths from multi-pollutant and single-pollutant models, respectively), Birmingham City (570-709 and 554 attributable deaths from multi-pollutant and single-pollutant models, respectively) and Greater Manchester (1,459 attributable deaths from the single-pollutant model [36]) and can be explained by the population, death rate (Table 12) and pollution level differences as above.

In all the cases discussed above, other factors may also be having an influence (see discussion of differences across constituencies in section 6.2).

Comparisons are more difficult with an earlier report in London (Walton *et al* 2015) as the methodology has changed to a greater extent and the time periods of the pollution changes are also different. The mortality burden result for the single pollutant model for $PM_{2.5}$ was 3,537 deaths at typical ages for 2010 compared with 210 attributable deaths for Bristol for 2011. Again, this difference is primarily driven by the larger population in London (8 million vs 0.5 million, London vs Bristol respectively).

In summary, this report shows the gains in life years from the projected pollution improvements but also that adverse health impacts will still remain. There is still justification for further pollution improvements beyond those already made, ultimately to achieve the lowest possible levels of pollution which would benefit all Bristol citizens greatly.

7.3 Ozone

This report does not consider ozone but some general comments can be made. The study from Williams et al. (2018a and 2018b) shows that ozone concentrations in 2035 and 2050 are projected to increase in winter because the removal of ozone by reaction with NO occurs to a lesser extent due to reductions in NOx emissions. So-called summer smog ozone concentrations are projected to decrease because of the reductions in emissions of ozone precursors. The Williams (2018a and 2018b) study found that the long-term ozone exposure metric recommended by WHO (2013) is projected to decrease over time compared with 2011. This outcome is a relatively small change compared with that for the other pollutants, due to the WHO threshold of 35 parts per billion and the effect being on respiratory mortality, not all cause mortality. Williams et al. (2018a and 2018b) also warned that the increased proportion of ozone in the mixture of oxidant gases, including NO_2, is potentially of some concern because ozone has a higher redox potential than does NO_2, and so could possibly increase the hazard from oxidative stress, although it is too early to be confident about this theory.

[36]Multi-pollutant model results not available for Greater Manchester

8.0 Appendix

8.1 Additional tables- method

Additional data such as the annualised economic impact and the loss of life expectancy lower and upper estimate and the full range of confidence interval with and without counterfactual for both $PM_{2.5}$ and NO_2 are available upon request to the authors.

Table 13 Concentration-response functions (CRFs) for long-term exposures and mortality (for impact calculations of general changes in pollutant concentrations (rather than policies targeting one pollutant alone) and for the single-pollutant model aspect of burden calculations).

Pollutant	Averaging time	Hazard ratio per 10 µg m^{-3}	Confidence interval	Counterfactual	Comment/Source
$PM_{2.5}$	Annual average	1.06	1.04-1.08 1.01-1.12*	Zero Or 7 µg m^{-3}	Age 30+, Anthropogenic $PM_{2.5}$ (Hazard ratio COMEAP (2010) and COMEAP (2018)) Age 30+, total $PM_{2.5}$ (cut-off reference COMEAP (2010))
NO_2	Annual average	1.023	1.008 – 1.037	Zero or 5 µg m^{-3}	Age 30+ (Hazard ratio COMEAP (2017), cutoff COMEAP (2018)

*This wider uncertainty is only used as an addition for the single-pollutant model aspect of burden calculations

Table 14 Concentration-response functions (CRFs) for long-term exposures and mortality burden from the four multi-pollutant model cohort studies including multi-pollutant model estimates

Pollutant	Averaging time	Hazard ratio per 10 µg m^{-3}	Counterfactual	Comment/Source
$PM_{2.5}$	Annual average	1.029 (Jerrett) 1.033 (Fischer) 1.053 (Beelen) 1.019 (Crouse)	Zero Or 7 µg m^{-3}	Age 30+, Anthropogenic $PM_{2.5}$ (Hazard ratio COMEAP (2010) and COMEAP (2018)) Age 30+, total $PM_{2.5}$ (cut-off reference COMEAP (2010))
NO_2	Annual average	1.019 (Jerrett) 1.016 (Fischer) 1.011 (Beelen) 1.020 (Crouse)	Zero or 5 µg m^{-3}	Age 30+ (Hazard ratio COMEAP (2017), cutoff COMEAP (2018))

*Derived from applying the % reduction on adjustment for the other pollutants in each individual study to the pooled single pollutant summary estimate as in COMEAP (2018a)

Table 15 Geographic scales of health impact calculations

Concentrations	Concentration output for health impacts	Population by gender and age group	Population-weighting	Mortality data	Impact calculations
1km	Ward	Ward	Ward to parliamentary constituency	Constituency	Sum of constituency results

8.2 Additional tables - impact

Table 16 Life years lost by gender across the parliamentary constituencies and Bristol City population for anthropogenic $PM_{2.5}$ (without cut-off)

Zone	Gender	Concentration does not reduce from 2011 levels			Predicted concentration between 2011 and 2030		
		Central estimate	Lower estimate	Upper estimate	Central estimate	Lower estimate	Upper estimate
Bristol East	Female	42,826	28,941	56,342	32,303	21,807	42,542
Bristol East	Male	48,951	33,072	64,415	36,908	24,911	48,614
Bristol North West	Female	45,734	30,892	60,193	32,016	21,602	42,186
Bristol North West	Male	46,961	31,688	61,871	32,766	22,093	43,204
Bristol South	Female	47,915	32,359	63,075	35,270	23,798	46,474
Bristol South	Male	54,538	36,807	71,843	40,083	27,032	52,842
Bristol West	Female	55,774	37,740	73,280	38,080	25,722	50,119
Bristol West	Male	73,048	49,330	96,166	49,634	33,482	65,412
Bristol City	Female	192,248	129,933	252,889	137,669	92,929	181,321
Bristol City	Male	223,498	150,897	294,296	159,391	107,518	210,071
Bristol City	Total	415,747	280,829	547,185	297,060	200,446	391,392

Table 17 Life years lost by gender across the parliamentary constituencies and Bristol City population for NO_2 (without cut-off)

Zone	Gender	Concentration does not reduce from 2011 levels			Predicted concentration between 2011 and 2030		
		Central estimate	Lower estimate	Upper estimate	Central estimate	Lower estimate	Upper estimate
Bristol East	Female	29,186	10,281	46,403	16,038	5,636	25,557
Bristol East	Male	33,450	11,780	53,196	18,360	6,451	29,261
Bristol North West	Female	32,882	11,579	52,293	16,200	5,690	25,826
Bristol North West	Male	33,729	11,860	53,714	16,485	5,787	26,295
Bristol South	Female	30,297	10,660	48,220	15,897	5,582	25,350
Bristol South	Male	34,761	12,220	55,368	18,173	6,379	28,990
Bristol West	Female	46,378	16,392	73,504	22,833	8,035	36,339
Bristol West	Male	60,841	21,433	96,719	30,025	10,550	47,849
Bristol City	Female	138,743	48,913	220,420	70,968	24,943	113,072
Bristol City	Male	162,781	57,293	258,998	83,043	29,167	132,394
Bristol City	Total	301,524	106,206	479,418	154,011	54,110	245,466

Table 18 Central annualised economic impact estimate (in 2014 prices) across the parliamentary constituencies and Bristol City population for anthropogenic $PM_{2.5}$ and NO_2 (without cut-off)

Zone	Anthropogenic $PM_{2.5}$		NO_2	
	Concentration does not reduce from 2011 levels	Predicted concentration between 2011 and 2030	Concentration does not reduce from 2011 levels	Predicted concentration between 2011 and 2030
	Central estimate	Central estimate	Central estimate	Central estimate
Bristol East	£52,096,726	£39,611,768	£35,547,621	£20,135,937
Bristol North West	£52,842,864	£37,352,199	£37,967,972	£19,339,922
Bristol South	£57,887,757	£42,963,077	£36,750,351	£19,873,955
Bristol West	£71,311,565	£48,909,777	£59,353,952	£29,968,278
Bristol City	£234,138,912	£168,836,821	£169,619,895	£89,318,091

Table 19 Lower and upper annualised economic impact estimate (in 2014 prices) across the parliamentary constituencies and Bristol City population for anthropogenic $PM_{2.5}$ and NO_2 (without cut-off)

Zone	Anthropogenic $PM_{2.5}$		NO_2	
	Predicted concentration between 2011 and 2030		Predicted concentration between 2011 and 2030	
	Lower estimate	Upper estimate	Lower estimate	Upper estimate
Bristol East	£26,735,354	£52,177,851	£7,075,466	£32,089,348
Bristol North West	£25,191,346	£49,238,176	£6,791,203	£30,840,015
Bristol South	£28,977,535	£56,630,290	£6,977,313	£31,697,496
Bristol West	£33,014,412	£64,418,931	£10,538,756	£47,723,402
Bristol City	£113,918,647	£222,465,248	£31,382,739	£142,350,261

Table 20 Life years lost by gender across the parliamentary constituencies and Bristol City for $PM_{2.5}$ (with 7 µg m^{-3} cut-off)

Zone	Gender	Concentration does not reduce from 2011 levels			Predicted concentration between 2011 and 2030		
		Central estimate	Lower estimate	Upper estimate	Central estimate	Lower estimate	Upper estimate
Bristol East	Female	18,378	12,391	24,233	7,442	5,012	9,823
Bristol East	Male	21,035	14,181	27,740	8,531	5,746	11,261
Bristol North West	Female	19,027	12,825	25,095	4,913	3,308	6,486
Bristol North West	Male	19,513	13,148	25,748	4,965	3,343	6,556
Bristol South	Female	19,020	12,819	25,090	5,898	3,972	7,787
Bristol South	Male	21,731	14,642	28,674	6,772	4,560	8,941
Bristol West	Female	26,543	17,910	34,973	8,235	5,547	10,868
Bristol West	Male	34,756	23,430	45,837	10,697	7,204	14,121
Bristol City	Female	82,968	55,945	109,392	26,487	17,839	34,963
Bristol City	Male	97,036	65,400	127,999	30,966	20,853	40,880
Bristol City	Total	180,004	121,345	237,391	57,453	38,692	75,843

Table 21 Life years lost by gender across the parliamentary constituencies and Bristol City population for NO_2 (with 5 µg m^{-3} cut-off)

Zone	Gender	Concentration does not reduce from 2011 levels			Predicted concentration between 2011 and 2030		
		Central estimate	Lower estimate	Upper estimate	Central estimate	Lower estimate	Upper estimate
Bristol East	Female	22,091	7,772	35,165	8,888	3,120	14,180
Bristol East	Male	25,350	8,916	40,361	10,202	3,581	16,276
Bristol North West	Female	25,165	8,851	40,066	8,420	2,955	13,437
Bristol North West	Male	25,802	9,065	41,122	8,513	2,986	13,588
Bristol South	Female	21,897	7,695	34,889	7,444	2,611	11,882
Bristol South	Male	25,230	8,862	40,223	8,596	3,015	13,722
Bristol West	Female	37,926	13,383	60,201	14,263	5,012	22,732
Bristol West	Male	49,766	17,514	79,190	18,857	6,620	30,077
Bristol City	Female	107,079	37,702	170,321	39,016	13,697	62,232
Bristol City	Male	126,147	44,357	200,896	46,168	16,202	73,663
Bristol City	Total	233,226	82,059	371,217	85,184	29,899	135,895

Table 22 Annualised economic impact (in 2014 prices) across the parliamentary constituencies and Bristol City population for $PM_{2.5}$ and NO_2 (with 7 μg m^{-3} and 5 μg m^{-3} cut-off for $PM_{2.5}$ and NO_2, respectively)

Zone	$PM_{2.5}$		NO_2	
	Concentration does not reduce from 2011 levels	Predicted concentration between 2011 and 2030	Concentration does not reduce from 2011 levels	Predicted concentration between 2011 and 2030
	Central estimate	Central estimate	Central estimate	Central estimate
Bristol East	£22,364,341	£9,411,950	£26,920,583	£11,450,991
Bristol North West	£21,964,406	£6,072,744	£29,048,057	£10,364,808
Bristol South	£23,017,788	£7,569,118	£26,618,639	£9,691,117
Bristol West	£33,934,882	£10,851,542	£48,545,185	£19,045,125
Bristol City	£101,281,417	£33,905,354	£131,132,464	£50,552,040

Table 23 Loss of life expectancy by gender across the parliamentary constituencies and Bristol City from birth in 2011 for anthropogenic $PM_{2.5}$ (without cut-off) and NO_2 (without cut-off)

Zone	Gender	Loss of life expectancy from birth compared with baseline mortality rates, 2011 birth cohort followed for 105 years (weeks)			
		Anthropogenic $PM_{2.5}$ (without cut-off)		NO_2 (without cut-off)	
		Concentration does not reduce from 2011 levels	Predicted concentration between 2011 and 2030	Concentration does not reduce from 2011 levels	Predicted concentration between 2011 and 2030
Bristol East	Female	30.6	22.8	20.9	10.8
Bristol East	Male	34.9	26.0	23.9	12.4
Bristol North West	Female	31.5	21.7	22.7	10.4
Bristol North West	Male	34.1	23.4	24.5	11.2
Bristol South	Female	30.5	22.1	19.3	9.6
Bristol South	Male	35.2	25.5	22.5	11.1
Bristol West	Female	31.1	21.0	25.9	12.2
Bristol West	Male	39.4	26.4	32.8	15.5
Bristol City	Female	30.9	21.9	22.3	10.8
Bristol City	Male	36.0	25.4	26.1	12.6

Table 24 Loss of life expectancy by gender across the parliamentary constituencies and Bristol City from birth in 2011 for anthropogenic $PM_{2.5}$ (with 7 µg m^{-3} cut-off) and NO_2 (with 5 µg m^{-3} cut-off)

Zone	Gender	Loss of life expectancy from birth compared with baseline mortality rates, 2011 birth cohort followed for 105 years (weeks)			
		Anthropogenic $PM_{2.5}$ (with 7 µg m^{-3} cut-off)		NO_2 (with 5 µg m^{-3} cut-off)	
		Concentration does not reduce from 2011 levels	Predicted concentration between 2011 and 2030	Concentration does not reduce from 2011 levels	Predicted concentration between 2011 and 2030
Bristol East	Female	13.2	5.0	15.8	5.7
Bristol East	Male	15.0	5.7	18.1	6.5
Bristol North West	Female	13.2	2.9	17.4	5.0
Bristol North West	Male	14.2	3.2	18.8	5.4
Bristol South	Female	12.1	3.4	14.0	4.2
Bristol South	Male	14.1	4.0	16.3	4.9
Bristol West	Female	14.8	4.3	21.2	7.4
Bristol West	Male	18.8	5.4	26.8	9.4
Bristol City	Female	13.4	3.9	17.2	5.6
Bristol City	Male	15.6	4.6	20.2	6.6

8.3 Additional tables – burden

Table 25 Estimated burden (from single-pollutant model summary estimate with wider estimates of uncertainty) of effects on annual mortality in 2011 of 2011 levels of anthropogenic $PM_{2.5}$ (with and without cut-off)

Zone	Anthropogenic $PM_{2.5}$ (without cut-off)			Anthropogenic $PM_{2.5}$ (with cut-off)		
	Attributable deaths			Attributable deaths		
	Central estimate	Lower estimate	Upper estimate	Central estimate	Lower estimate	Upper estimate
Bristol East	50	9	94	22	4	42
Bristol North West	66	12	125	28	5	54
Bristol South	59	10	111	23	4	45
Bristol West	36	6	68	17	3	33
Bristol City	211	37	398	90	16	174

Using COMEAP's recommended concentration-response coefficient of 1.06 per 10 µg m^{-3} of anthropogenic $PM_{2.5}$ for the central estimate (lower estimate RR of 1.01 and upper estimate RR 1.12)

Table 26 Estimated burden (from the estimates derived by using information from multi-pollutant model results from 4 different cohort studies) of effects on annual mortality in 2011 of 2011 levels of anthropogenic $PM_{2.5}$ and NO_2 (with cut-off), total population in each constituency in 2011, mortality rate (total death age 30 plus divided by total population age 30 plus) in each constituency, ratio of the population age 65 and above over the total population in each constituency and deprivation index Carstairs quintiles[37]

Zone	Anthropogenic $PM_{2.5}$ and NO2 (without cut-off)	Total population	Mortality rate (age group 30 plus)	Ratio Population above 65 when compared with total population	Carstairs quintile
	Attributable deaths (using coefficients derived from information in 4 studies below*)				
Bristol East	47 - 61	95,373	1.26%	15%	3.6
Bristol North West	64 - 82	100,814	1.61%	17%	3.2
Bristol South	51 - 70	107,370	1.41%	15%	4.1
Bristol West	38 - 47	124,698	0.83%	7%	3.3

*Using COMEAP's recommended concentration-response coefficient of 1.029, 1.033, 1.053 and 1.019 per 10 µg m^{-3} of anthropogenic $PM_{2.5}$ derived by applying to a single pollutant model summary estimate the % reduction in the coefficient on adjustment for nitrogen dioxide from the Jerrett *et al* (2013), Fischer *et al* (2015), Beelen *et al* (2014) and Crouse *et al* (2015) studies , respectively

*Using COMEAP's recommended concentration-response coefficient of 1.019, 1.016, 1.011 and 1.020 per 10 µg m^{-3} of NO_2 derived by applying to a single pollutant model summary estimate the % reduction in the coefficient on adjustment for $PM_{2.5}$ from the Jerrett *et al* (2013), Fischer *et al* (2015), Beelen *et al* (2014) and Crouse *et al* (2015) studies , respectively

[37] Acknowledgement to Dr Daniela Fecht (Imperial College London) for formatting Carstair Quintiles data by Wards
https://www.researchgate.net/publication/6817786_Measuring_deprivation_in_England_and_Wales_using_2001_Carstairs_scores

Table 27 Estimated burden (from multi pollutant study) of effects on annual mortality in 2011 of 2011 levels of anthropogenic $PM_{2.5}$ and NO_2 (without cut-off)

Zone	Anthropogenic $PM_{2.5}$ (without cut-off) (not to be used separately)				NO_2 (without cut-off) (not to be used separately)				Anthropogenic $PM_{2.5}$ and NO2 (without cut-off) (combined estimate has less uncertainty)			
	Attributable deaths				Attributable deaths				Attributable deaths			
	Jerrett	Fischer	Beelen	Crouse	Jerrett	Fischer	Beelen	Crouse	Jerrett	Fischer	Beelen	Crouse
Bristol East	25	28	44	17	28	24	17	30	53	52	61	47
Bristol North West	33	38	59	22	40	34	23	42	73	72	82	64
Bristol South	29	33	52	19	31	26	18	32	60	59	70	51
Bristol West	18	20	32	12	25	21	15	26	43	41	47	38
Bristol City	105	120	188	70	124	105	73	130	229	225	261	200

Using COMEAP's recommended concentration-response coefficient of 1.029, 1.033, 1.053 and 1.019 per 10 µg m^{-3} of anthropogenic $PM_{2.5}$ derived by applying to a single pollutant model summary estimate the % reduction in the coefficient on adjustment for nitrogen dioxide from the Jerrett *et al* (2013), Fischer *et al* (2015), Beelen *et al* (2014) and Crouse *et al* (2015) studies , respectively

Using COMEAP's recommended concentration-response coefficient of 1.019, 1.016, 1.011 and 1.020 per 10 µg m^{-3} of NO_2 derived by applying to a single pollutant model summary estimate the % reduction in the coefficient on adjustment for $PM_{2.5}$ from the Jerrett *et al* (2013), Fischer *et al* (2015), Beelen *et al* (2014) and Crouse *et al* (2015) studies , respectively

Table 28 Estimated burden (from multi pollutant study) of effects on annual mortality in 2011 of 2011 levels of anthropogenic $PM_{2.5}$ and NO_2 (with cut-off)

Zone	Anthropogenic $PM_{2.5}$ (with cut-off) (not to be used separately)				NO_2 (with cut-off) (not to be used separately)				Anthropogenic $PM_{2.5}$ and NO2 (with cut-off)			
	Attributable deaths				Attributable deaths				Attributable deaths			
	Jerrett	Fischer	Beelen	Crouse	Jerrett	Fischer	Beelen	Crouse	Jerrett	Fischer	Beelen	Crouse
Bristol East	11	12	19	7	21	18	13	23	32	30	32	30
Bristol North West	14	16	25	9	31	26	18	32	45	42	43	41
Bristol South	12	13	21	8	22	19	13	23	34	32	34	31
Bristol West	9	10	15	6	20	17	12	21	29	27	27	27
Bristol City	45	51	80	30	95	80	55	99	140	131	135	129

Using COMEAP's recommended concentration-response coefficient of 1.029, 1.033, 1.053 and 1.019 per 10 µg m^{-3} of anthropogenic $PM_{2.5}$ derived by applying to a single pollutant model summary estimate the % reduction in the coefficient on adjustment for nitrogen dioxide from the Jerrett *et al* (2013), Fischer *et al* (2015), Beelen *et al* (2014) and Crouse *et al* (2015) studies , respectively

Using COMEAP's recommended concentration-response coefficient of 1.019, 1.016, 1.011 and 1.020 per 10 µg m^{-3} of NO_2 derived by applying to a single pollutant model summary estimate the % reduction in the coefficient on adjustment for $PM_{2.5}$ from the Jerrett *et al* (2013), Fischer *et al* (2015), Beelen *et al* (2014) and Crouse *et al* (2015) studies , respectively

8.4 Additional Health and economic assessment methods

Anthropogenic $PM_{2.5}$: Non-anthropogenic $PM_{2.5}$ was derived by subtracting the modelled contribution from natural sources – here sea-salt - from the total $PM_{2.5}$ modelled as above to give anthropogenic $PM_{2.5}$.

Population data in Bristol: 2011 census data by ward by 5 year age group and gender (ONS, 2012) was split into 1 year age groups using the age ratios from single year of age and gender population data, by LSOA, for mid-2012 (ONS, 2016a).

Deaths data in Bristol: Deaths data by gender and 5 year age group by ward for 2011 was obtained on request from ONS (ONS, 2016b). It was scaled to 1 year age groups using age group ratios from data by LSOA by single year of age and gender for mid-2014 (ONS, 2016c). Ward data was then aggregated up to constituency level.

<u>Mortality Burden</u>

The calculations followed COMEAP (2018a) and earlier methodology from COMEAP (2010) and Gowers et al (2014).

Using the COMEAP (2010)/Gowers *et* al (2014) methodology as the first example, the relative risk (RR) per 10 µg m^{-3} was scaled to a new relative risk for the relevant anthropogenic $PM_{2.5}$ concentration. The equation used was:

RR(x) = 1.06x/10 where x is the average concentration of interest.

The new RR(x) was then converted to the attributable fraction (AF) using the following formula:

AF = (RR-1)/RR multiplied by 100 to give a percentage.

The attributable fraction was then multiplied by the number of deaths in the relevant gender and 5-year age group aged 30+ to give the number of attributable deaths.

The attributable deaths were then summed across the 5-year age groups above aged 30, for both males and females, to give a total for each ward.

The calculations above were done at ward level and the results for deaths summed to give a total for each constituency. This allows different death rates in different wards and constituency to influence the results.

The process was repeated for the lower and upper confidence intervals around the relative risks, and for a cut-off of 7 µg m^{-3} $PM_{2.5}$.

The COMEAP (2018a) methodology uses the above method for $PM_{2.5}$ but also calculates a result using a single-pollutant model relative risk for NO_2 and a result combining multi-pollutant model estimates for NO_2 and $PM_{2.5}$.

The method for the single-pollutant model calculation for NO_2 is exactly analogous to that above for $PM_{2.5}$ except that the relative risk used is 1.023 (1.008 – 1.037) and the cut-off where used is 5 µg m^{-3} NO_2.

The method using multi-pollutant model results is also based on the same method for scaling the relevant relative risks (see Table 10) according to the relevant pollution concentration. In this case though, there are more calculations (16) because calculations are done separately for each pollutant for relative risks derived from each of 4 studies, both with and without the relevant cut-off for each pollutant. There is also an additional step in that the NO_2 and $PM_{2.5}$ results within each study are summed and then the final result expressed as the range for the sums across the 4 studies. This can be illustrated by examining Table 27 and Table 28 (with and without the cut-offs). It can be seen for Halton, for example, that the sum of column 2 (34 attributable deaths) and column 6 (42 attributable deaths) leads to the result in column 10 (76 attributable deaths). In this example, the results in columns 2 and 6 should be regarded only as intermediate steps in the calculation as it may be that one is over-estimated and the other under-estimated. This is thought to cancel out for the summed result, which is therefore more robust.

Mortality Impact

Projections for the baseline life tables before applying concentration changes

Natural change – current population size, age distributions and mortality rates will generate future changes in population and age structure in any case. We did not add this separately as it is already taken into account in our life table modelling.

Changes in births over time – actual data on numbers of births in each local authority was used from 2011-2015 (ONS, 2016d), birth projections by local authority were used from 2016 to 2033 (ONS, 2016e) and the ratio of birth projections to 2039 births for England obtained from national populations projections (ONS, 2015a) was used to scale 2039 births in local authorities to local authority births for 2040 to 2114. No projections were available after 2114 so births were left constant for 2115 to 2134.

Mortality rate improvements were applied to the 2011 all-cause hazard rates according to the projected % improvements per year provided by ONS. Percentage improvements for different example ages are provided in Office for National Statistics (ONS, 2015b); we requested the full set of percentage improvements from ONS.

Migration – predicting migration at the current time post the European referendum is particularly uncertain with both increases and decreases forecast. We did not therefore include this in our first analyses as presented in this report. Over the country as a whole this contribution to overall health impacts is likely to be small. This can be explored further in future work.

Lags: The approach allowed for a delay between exposure and effect using the recommended distribution of lags from COMEAP (COMEAP, 2010) i.e. 30% of the effect in the first year, 12.5% in each of years 2-5 and 20% spread over years 5-20. An analogous approach was used for the effects of long-term exposure to NO_2. HRAPIE (WHO, 2013) recommended that, in the absence of information on likely lags between long-term exposure to NO_2 and mortality, calculations should follow whatever lags are chosen for $PM_{2.5}$.

Calculations

The relative risk (RR) per 10 µg m^{-3} was scaled to a new relative risk for the appropriate population-weighted mean for each gender in each constituency for each scenario and year. The equation used (for the example coefficient of 1.06) was: RR(x) = 1.06x/10 where x is the concentration of interest (with a negative sign for a reduction). Concentrations were assumed to reduce linearly between the years in which modelled concentrations were available (2011, 2017, 2020, 2025, 2030). The scaled RR was then used to adjust the all-cause hazard rates in the life table calculations.

For the 5 µg m^{-3} cut-off for NO_2, ward concentrations were interpolated between 2011, 2017, 2020, 2025 and 2030 and 5 µg m^{-3} was then subtracted from the ward concentrations in each year. Any resulting negative concentrations were then set to zero before all the ward concentrations were population-weighted to constituency level as normal.

Life table calculations were programmed in SQL based on the methods used in the standard IOMLIFET spreadsheets [132] with the following amendments:

- Extension to 2134 (105 years after 2030)
- Adjustment of the baseline hazard rates over time according to projected mortality rate improvements
- Inclusion of changes in numbers of births over time
- IOMLIFET excludes neonatal deaths. We included neonatal deaths and followed the South East Public Health Observatory life-expectancy calculator[38] and Gowers et al. (2014) in taking into account the uneven distribution of deaths over the course of the first year when calculating the survival probability. (The survival probability (the ratio of the number alive at the end of the year to the number alive at the beginning) is derived by the equivalent of adding half the deaths back onto the mid-year population to give the starting population and subtracting half the deaths from the mid-year population to give the end population, assuming deaths are distributed evenly across the year. This is not the case in the first year where a weighting factor based on 90% of the deaths occurring in the first half of the year and 10% in the second half is used instead. After

[38] https://webarchive.nationalarchives.gov.uk/20130329125326/http://www.lho.org.uk/viewResource.aspx?id=8943&sUri=http%3a%2f%2fwww.sepho.org.uk%2f

rearrangement the actual formula is (1- 0.1 x hazard rate)/(1+ 0.9 x hazard rate) rather than the (1- 0.5 x hazard rate)/(1+ 0.5 x hazard rate) used in other years.)

Results for total and annual life years lost by constituency were then summed to Bristol level. We also used the life tables to calculate changes in life expectancy.

Economic valuation[39]

The approach taken here is based on the discipline of environmental economics (ExternE, 2005). Environmental economics was developed partly in response to recognition of the externalities, or external costs, posed by various human activities. 'Externalities' are unforeseen effects that arise from action that benefits one party generally to the detriment of others, when those effects are external, or not considered, in the decision-making process. Notable examples include the loss of utility from effects of air pollution arising from power generation or transport. The question faced by the economist in this situation is not how to allocate a defined amount of resource (the health service budget), but how much should be spent to mitigate externalities. This requires that health impacts are monetised in order that the benefits of action can be compared directly with the costs in a benefit-cost analysis.

Several approaches have been taken to value mortality impacts (the impacts that dominate the assessment made in this report), though all seek to quantify public preference, demonstrating consistency in objective with the health economics work in deriving QALYs for various conditions. The methods used for valuing a death fall into three categories:

Wage-risk studies, which consider the additional wage demanded of people working in risky occupations, providing an estimate of willingness to accept (WTA) risk.

Consumer market studies, that consider the willingness of individuals to pay (WTP) for equipment that will reduce their risk of death. Several studies were carried out on car safety equipment (air bags, etc.) before they were made mandatory.

Contingent valuation (CV) surveys, where individuals are asked for their WTP for treatments that will reduce the risk of a health impact of some kind, or of dying within X years.

Early work in this field was affected by various biases. Considerable effort has been taken over the last three decades to identify these biases and refine CV approaches to reduce them, with some success.

In the context of health valuation, the underlying calculations are similar whichever of the three methods just mentioned is used. In the case of the wage risk studies, for example, it may be observed that construction workers operating at height will accept an additional risk of death annually of 1 in 1,000 (0.001), for an additional wage of £1000. The value of statistical life (VSL) calculated from these figures would be £1000/0.001 - £1,000,000. A review by OECD gives an averaged VSL for EU Member States of €3million. UK Government, via the Department for Transport, adopts a value that is lower by about 40% of £1.56 million (DfT, 2017).

Opinion is divided as to whether valuation of mortality should concern 'deaths' or 'life years lost'. The OECD is firmly committed to use of the VSL (OECD, 2012). UK government, through the Interdepartmental Group on Costs and Benefits, however, values mortality in terms of the loss of life expectancy expressed as the 'Value of a Life Year' (VOLY), taking a value of £36,379 in 2014 prices. The basic approach to quantification, however, is the same, with values elicited against a change in the risk of a health outcome, in this case, the loss of a life year. The large difference between the unit values for VSL and VOLY is partly mitigated in subsequent analysis by the number of life years lost being about 10 times higher than the number of deaths. However, the UK government position generates estimates of air pollution damage that are significantly lower than estimates made using the OECD position. Given that the UK government position is followed here, results should be considered to be at the conservative end of plausible ranges.

Similar calculations can be made to assess the WTP to avoid ill health more generally, such as development of respiratory or cardiovascular disease. The total impact for morbidity has a number of elements:

WTP to avoid lost utility (being well, and enjoying the opportunities that good health offers)

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[39]Much of this section is sourced from text written by Mike Holland in Williams et al (2018b).

Adopted values, discounting and uplift

The values of most relevance concern acute and chronic mortality, as these have been shown by numerous studies to dominate the CBA. The value of a lost year of life to chronic exposure as applied in the current analysis is £36,379, assuming that it reflects the loss of a year of life in 'normal health' taken from the guidance issued by Defra (2019).

It is important to factor the time at which impacts occur into the analysis for two reasons. The first is that values should be uplifted for future years to capture the likely effect of (anticipated) growth in incomes on WTP for health protection. The second, opposing effect, concerns the need to discount future values on the basis that money or goods are more valuable now than at some point in the future. There are several reasons for this. One is that resource available now can be used to increase the availability of resource in the future. An obvious example concerns investment in infrastructure projects that facilitate economic development. Along similar lines, investment in health research may lead to the development of cures or treatments for illnesses in the future. Further information can be found in Guidance from Her Majesty's Treasury in the 'Green Book' (HMT, 2018).

The Green Book recommends the use of declining discount rates for effects quantified over prolonged periods. However, the impact of using declining discount rates in line with the HMT recommendation, rather than constant discount rates, will be minimal as they apply only after 30 years have passed, by which time values are reduced by two thirds. The impact of the declining rates will clearly increase over time, though the rate of decline (see Table 29) is so slight this will still make little difference.

Table 29 Schedule of declining long-term discount rates from HMT, 2018

Period of years	Discount rate
0 – 30	3.5%
31 – 75	3.0%
76 – 125	2.5%
126 – 200	2.0%
201 – 300	1.5%
301+	1.0%

The government guidance (HMT, 2019) recommends that future values should be uplifted at 2% per annum given that "It is expected that as people's incomes rise, so too does their willingness to pay to reduce health risks such as those associated with air pollution." However, it is unclear whether the uplift of 2% is still appropriate. It is notable that it was first developed before the economic crash of 2008, and so does not account for any change in growth since that time. However, the present analysis is based on a long time-frame, so short-term perturbations to growth seem likely to be factored out in the longer term.

Inequality is not factored explicitly into the economic analysis, beyond the acceptance of a national average estimate for mortality valuation (in other words, the values of disadvantaged groups are not down rated to reflect a likely lower WTP linked to reduced ability to pay).

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