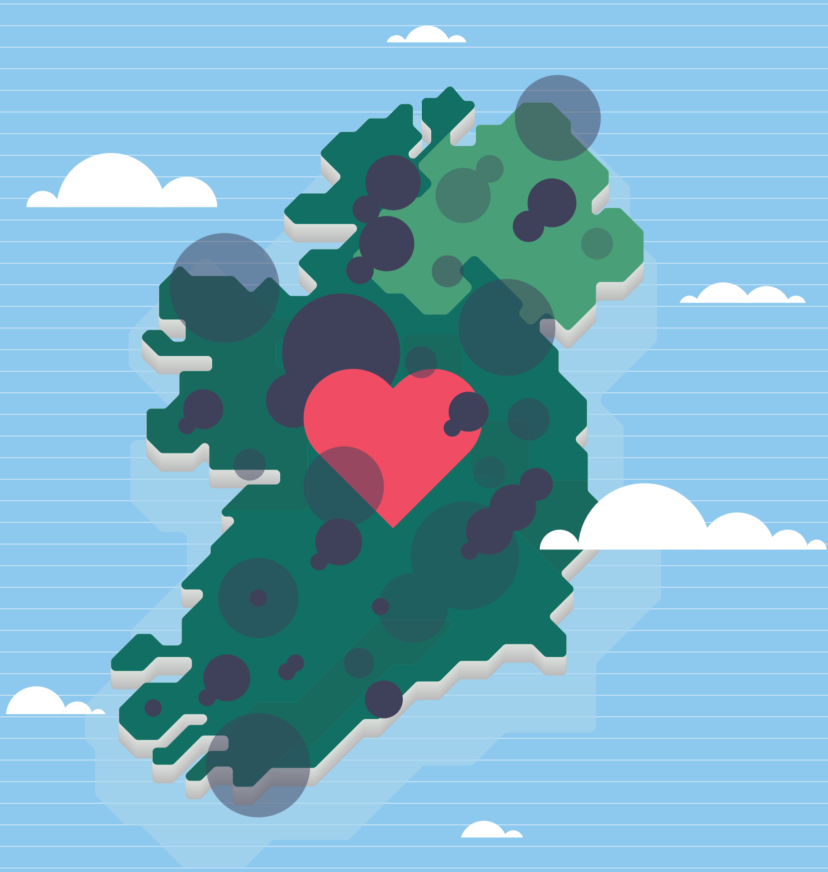
AIR POLLUTION AND MORTALITY ON THE ISLAND OF IRELAND

Estimating Local All-Cause and Circulatory Mortality Burdens Associated with Fine Particulate Matter Pollution in Northern Ireland and the Republic of Ireland



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Irish Heart Foundation

British Heart Foundation Northern Ireland

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Community Foundation Ireland

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A report commissioned by The Irish Heart Foundation on behalf of The Irish Heart Foundation and The British Heart Foundation

Foreword

Cardiovascular diseases (CVD) are the leading cause of death globally, taking an estimated 17.9 million lives each year. In the UK and Ireland, the British Heart Foundation (BHF) and the Irish Heart Foundation (IHF) are leading the fight against these diseases. Together as part of the European Heart Network we work with other foundations and associations dedicated to preventing cardiovascular diseases, supporting patients, representing patient interests and funding research.

The World Health Organization (WHO) estimates that in 2019, some 37% of outdoor air pollution-related premature deaths were due to ischaemic heart disease and stroke. We know that across the island of Ireland, poor air quality is continuing to have a detrimental impact on public health. That is why we have joined forces, to highlight the problem of air pollution and advocate for policy change to improve air quality, that will ultimately improve heart health for everyone.

In July 2021 we were successful in receiving funding from the Community Foundation All Island Communities Fund. Through this project we want to inform communities both across the island about the cardiovascular impacts of air pollution and influence elected representatives to implement changes to improve air quality on the island for the benefit of all our health. Air pollution is a transboundary issue, a common problem that we are working on collaboratively.

We have entrusted the team at Queen's University Belfast, led by Professor Duncan McVicar and Professor Patrick Goodman at Technological University Dublin to carry out this research into air pollution and mortality on the island of Ireland. We thank them for their time and dedication to this project.

The findings within this report make for stark reading and serve to shed some light on the size of the problem of air pollution on this island. With this information, we hope that decision makers on the island will utilise it to move forward with bold action on air pollution to protect our health.

Air pollution does not respect borders, therefore, to truly improve our air quality, governments must work together with co-ordinated policy interventions and legislation to protect our health.

Fearghal McKinney

Head of British Heart Foundation Northern Ireland

Tim Collins

Chief Executive, Irish Heart Foundation

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Executive Summary

Air Quality on the island of Ireland, north and south, is generally better than in Great Britain and much of mainland Europe. However, people are still being exposed to harmful levels of fine particulate air pollution ($PM_{2.5}$), most of which comes from combustion in various settings, including home heating and transport.

Using data from 2019, the most recent year unaffected by COVID-19, this report estimates the number of premature deaths associated with fine particulate air pollution on the island of Ireland. For the first time, estimates are presented both at the county level in the Republic of Ireland (ROI) and local government district (LGD) level in Northern Ireland (NI), as well as for the whole of ROI and the whole of NI.

We estimate that approximately 1,700 premature deaths (680 from cardiovascular disease) in the ROI, and 900 (with 300 from cardiovascular disease) in NI are attributable to exposure to fine particulate air pollution. Although the estimated mortality burden of air pollution is highest in Belfast and Dublin, there are attributable deaths in all counties and LGDs across the island of Ireland. These mortality estimates are higher than those published by the European Environment Agency (EEA) or the Global Burden of Disease Study for ROI in 2019, and by either Public Health England (PHE) for NI in 2010 or the Global Burden of Disease for NI in 2019. This reflects our use of updated dose response functions based on growing research evidence that exposure to $PM_{2.5}$ is more harmful than previously thought.

The World Health Organization (WHO) recommends air quality guideline (AQG) levels for air pollutants, including $PM_{2.5}$, above which there is clear evidence for damage to human health. The current WHO guideline level for $PM_{2.5}$ is an annual average of 5 $\mu g/m^3$ (5 micrograms per cubic metre). Many people living on the island of Ireland are exposed to air pollution levels well in excess of this level. This report estimates that there would be almost 1,000 per year fewer premature deaths attributable to air pollution on the island of Ireland if we were to achieve fine particulate matter pollution levels in line with this WHO guideline level. Reductions in $PM_{2.5}$ air pollution can also reduce morbidity alongside mortality.

The good news is that $PM_{2.5}$ pollution levels have generally been falling, albeit slowly, across the island of Ireland in recent years, and measures to further reduce air pollution are either already planned or under consideration. But more needs to be done and many lives could be saved by moving faster. Additional policy interventions to help achieve this, in particular from reducing fossil fuel burning, especially of the dirtiest fuels, would also have the added benefit of reducing our carbon footprint.

Background to the Report: Air Pollution, Fine Particulate Matter and Health

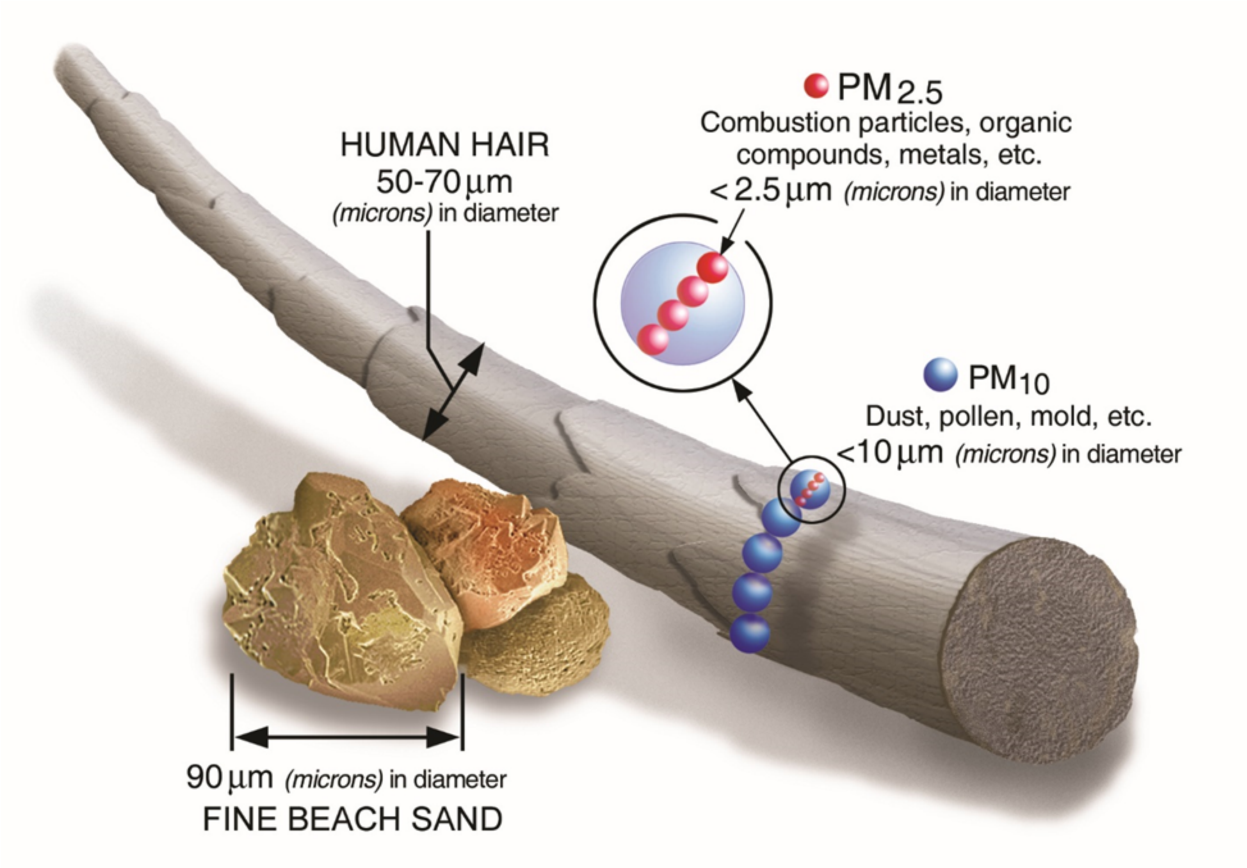
When we think of air pollution, we might conjure up images of the terrible smogs in London in the 1950s, or the severe pollution events more recently seen in China, with areas covered by thick dark smoke. Such extreme events of air pollution are associated with many excess deaths. For example, the UK government estimates that there were over 4,000 excess deaths during the peak week of the London smog in 1952 [1]. More recent research suggests that figure might have been closer to 12,000 excess deaths [2]. Here on the island of Ireland we witnessed many excess deaths in Dublin during a severe pollution episode in 1982 [3].

In 1980s Dublin, domestic coal burning was identified as the major source of pollution and, following a campaign, a ban on the 'marketing, sale and distribution of smoky coal' was introduced. There was an immediate and dramatic effect on air quality, and simultaneously there was a reduction in deaths [4]. Since then, the 'coal ban' has been extended to other parts of the Republic of Ireland (ROI) on a stepwise basis, and each time air quality has improved, and so too have health outcomes [5]. However, air pollution due to coal burning has continued to be a problem in smaller towns and villages not covered by the ban [6]. The hope is that this will now change following the introduction of nationwide restrictions on solid fuels from 31st October 2022 [7].

Similar local-level restrictions have been introduced in Northern Ireland. The Clean Air (NI) Order of 1981 introduced controls for the emission of smoke in urban areas. Under the Order, district councils can declare parts of their district as Smoke Control Areas, within which the emission of smoke from a premises, and the burning of 'unauthorised fuels' such as 'smoky' coal, is prohibited. Although much of Belfast city is covered, declarations are limited elsewhere, and so household coal burning continues to present a problem for air quality across much of NI [8].

Nowadays on the island of Ireland we do not generally see the thick clouds of smoke. But air pollution is not a problem confined to the past. Although air pollution now tends to be invisible to the human eye (at least at ground level), it is still present. Such pollution can come from natural sources, such as sea spray, forest/gorse fires, pollen, or even volcanoes. But it is human-generated air pollution – *anthropogenic* air pollution – which is the biggest concern. The main sources of air pollution from human activity are associated with combustion of fossil fuels, e.g. from petrol and diesel use in transport, or from domestic heating systems, in particular the burning of coal, wood and turf. Every time we burn something we are releasing particles into the air which are damaging to health.

The technical term for these small particles is fine particulate matter, or $PM_{2.5}$ for short. If these small particles are present in the air we breathe then they are small enough to enter into our lungs, and from there they can enter our bloodstream. Prolonged exposure to such particles can eventually lead to them causing damage to our pulmonary and cardiovascular systems. These harmful pollutants can damage blood vessels, causing them to become narrower and harder, and can also cause abnormal heart rhythms and increase blood pressure, increasing the risk of potentially deadly heart attacks and stroke [9].



Source: United States Environmental Protection Agency.

This report focuses on *outdoor* $PM_{2.5}$ air pollution, also sometimes called ambient air pollution. But it is important to remember that we can also be exposed to fine particular matter air pollution when we're indoors, and indoor air pollution can also be detrimental to health [10]. Fine particulate matter is also not the only air pollutant with detrimental effects on human health; the air is a complex mixture of different pollutants, including (among others) nitrogen dioxide (NO_2), a gas heavily associated with emissions from vehicles, especially diesel vehicles. However, $PM_{2.5}$ is considered to be one of the most harmful air pollutants [11].

On a global scale the WHO lists poor air quality as one of the world's leading causes of avoidable disease and premature death, attributing 4.2 million deaths worldwide per year to exposure to outdoor air pollution [12]. This problem is most acute in low- and middle-income countries, but outdoor air pollution is also a leading environmental risk factor in the developed world, including in Europe, and also here on the island of Ireland. For example, the EEA estimates that exposure to fine particulate matter led to approximately 307,000 premature deaths in the 27 European Union (EU) Member States, with 1,300 premature deaths in the ROI, in 2019 [13]. Public Health England estimates that there were approximately 550 premature deaths in NI in 2010 due to anthropogenic fine particulate matter exposure [14]. Other more recent estimates for NI suggest air pollution continues to lead to hundreds of premature deaths per year.

These premature deaths, along with the many others who experience long-term poor health associated with exposure to air pollution, add to human suffering. They also place a significant burden on our health services and wider society. For example, the Organisation for Economic Co-operation and Development (OECD) has predicted that inaction on outdoor air pollution could cost up to 1% of global gross domestic product (GDP) by 2060 [15].

When it comes to the ambient air we breathe, as individuals we don't really have much choice: we have to breathe the air where we live and work (and in between). However, together at local, regional, national and international levels – air pollution generated in one place can spread to neighbouring places – we do have choices. Although there is no 'safe' level of fine particulate air pollution [16], there is now a significant body of evidence to show that if air quality is improved, e.g. through reduced fossil fuel burning, fewer people die prematurely, and fewer people get ill [17]. This can help to reduce human suffering as well as reducing other social costs associated with ill health and premature death. A further benefit to reducing particulate air pollution through reduced fossil fuel usage is that it would reduce greenhouse gas emissions and thereby contribute to efforts to reduce climate change [18].

In this report, we first show the levels of outdoor $PM_{2.5}$ air pollution experienced by people living in NI and ROI, as of 2019. We use 2019 data because it is the most recent year of available data that is complete and not impacted by the COVID-19 pandemic. We also present data on average air pollution exposure experienced at the local level, specifically at the county level (ROI) and LGD level (NI), to help inform policy makers at the local government level as well as the national and cross-government levels. The data suggest that, in 2019, although average pollution exposures in all ROI counties and all NI LGDs met the relevant legal limits, they everywhere exceeded the most recent (2021) WHO AQG level for $PM_{2.5}$ [19], above which there is compelling evidence for harm to human health.

The second part of this report provides estimates of the number of premature deaths in 2019 associated with exposure to outdoor $PM_{2.5}$ air pollution, for ROI, for NI and for each county/LGD within ROI and NI. We do so by following the health impact assessment methodology recommended by the Committee on the Medical Effects of Air Pollutants (COMEAP) [20]–[22] and Public Health England [14]. Using this approach, we estimate that there were over 2,600 premature deaths across the island of Ireland associated with exposure to ambient $PM_{2.5}$ air pollution in 2019 – over 900 in NI and almost 1,700 in ROI – with more than 200 deaths in both Belfast and Dublin.

The final part of this report presents a number of hypothetical scenarios where we consider differing levels of $PM_{2.5}$ pollution – three that are lower than 2019 levels but also one scenario where the pollution level is higher – and estimate the numbers of premature deaths attributable to $PM_{2.5}$ air pollution in each scenario. For example, we estimate that achieving air pollution levels across the island of Ireland in line with the 2021 WHO AQG level would, in the long run, save around 1,000 lives per year.

We recognise that efforts to further reduce air pollution on the island of Ireland will involve trade-offs. For example, we are aware of the potential difficulties that might be experienced by those solely reliant on solid fuels for domestic heating were restrictions on solid fuel burning to be further extended. Household burning of solid fuel in urban areas of Northern Ireland is more common than in urban areas in the rest of the UK, for example, and many households are still reliant on oil as their sole source of central heating. Burning solid fuels was the primary method of heating for 3% of households, and a secondary method for 72% of households in 2016/17 in Northern Ireland [23].

We also write this report at a time of acute concerns over fuel poverty. As a result, we stop short of proposing specific policy interventions; such recommendations require detailed evaluations, which are outside the scope of this report. Nevertheless, alongside the hypothetical air-pollution-reduction scenarios presented here, we also briefly discuss a number of possible real-world interventions that could, if implemented, substantially reduce $PM_{2.5}$ air pollution on the island of Ireland.

A Brief Summary of Data Sources and Methods

This section briefly describes the datasets and methods used to calculate the mortality burden of $PM_{2.5}$ exposure in this report. There are three steps to this process: (i) generating pollution exposure data at the county/LGD level across the island of Ireland, (ii) sourcing mortality data at the county/LGD level across the island of Ireland, and (iii) estimating the proportion of deaths in each area that can be associated with long-term exposure to ambient $PM_{2.5}$ air pollution. Our approach follows PHE [14] (although our estimates do not distinguish between anthropogenic and other sources of $PM_{2.5}$) and the methodological recommendations of COMEAP [20]–[22]. A more detailed technical discussion is presented in Appendix 2.

Step 1: The EEA provides modelled data on annual average ambient $PM_{2.5}$ concentrations (in micrograms per cubic meter) at the 1x1km grid square level across the island of Ireland for 2019, along with 2019 resident population data for each grid square [24]. To generate county- and LGD-level population-weighted pollution data for 2019 we aggregate these grid square pollution data to the county/LGD level, taking account of differences in population concentrations within each area, i.e. accounting for the fact that the population within a county or LGD is not distributed evenly across its area. The resulting figures – population-weighted annual $PM_{2.5}$ concentrations – are interpretable as the ambient $PM_{2.5}$ pollution levels experienced on average by people living in that county/LGD, averaged over the whole of 2019.

Step 2: Area-level counts of the number of deaths in 2019 were obtained for NI from the Northern Ireland Statistics and Research Agency (NISRA) [25], [26] and for ROI from the Central Statistics Office (CSO) [27]–[29]. We then subtract the number of external deaths (e.g. deaths due to accidents or injury) from the total of all-cause deaths as the former cannot be caused by pollution exposure. We also use data on the number of deaths specifically due to diseases of the circulatory system, where such deaths are classified using International Classification of Diseases 10th Revision (ICD-10) codes I00-I99 in NI and I00-I97 in ROI.

Step 3: Estimating the mortality burden from exposure to ambient air pollution in each area involves combining data on pollution levels and deaths in each area with an estimate of the increase in mortality risk due to $PM_{2.5}$ exposure. Epidemiological studies typically quantify this pollution effect on mortality risk in terms of the relative risk (RR) per 10 $\mu g/m^3$ increase in $PM_{2.5}$, i.e. how much higher the risk of mortality would be were a population exposed to long-term $PM_{2.5}$ levels that were 10 $\mu g/m^3$ higher on average. We use estimated RRs recommended by COMEAP [22] – one for all-cause mortality

(1.08) and another for circulatory-related mortality (1.11) – which are based on an extensive assessment of relevant epidemiological research. After scaling these RRs by the level of air pollution in each area, we then generate an estimate of the percentage of deaths in each area that are associated with air pollution, known as the a*ttributable fraction* (AF). To generate estimates of the *number* of deaths attributable to long-term $PM_{2.5}$ exposure in each area we multiply the AFs by the total number of (non-external) deaths or total number of circulatory-related deaths in each area. Note that we use the terms 'attributable' deaths and 'premature' deaths interchangeably.

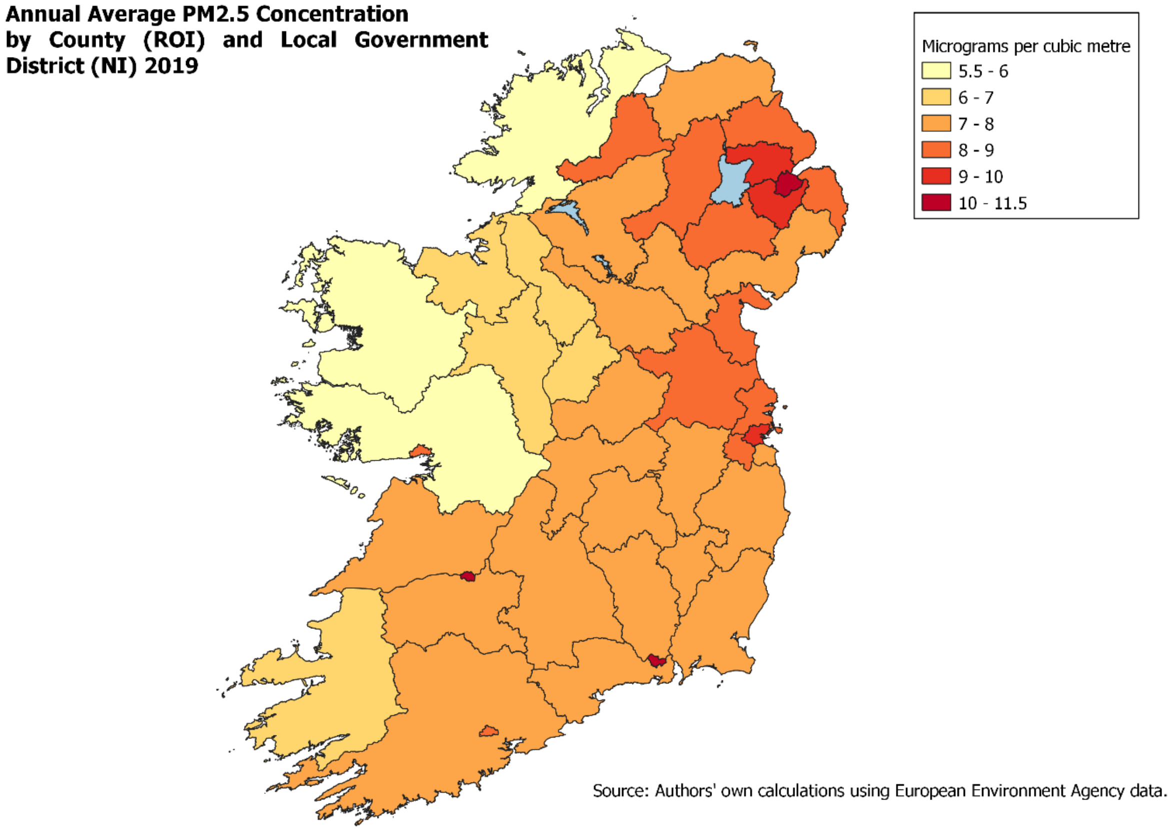
It is important to stress that the resulting estimates do not give a headcount of the number of deaths that actually occurred in each area in 2019 because of $PM_{2.5}$ exposure. Rather, they indicate that the level of $PM_{2.5}$ air pollution in that area increased mortality risk in the local population by an amount equivalent to this number of deaths.

In addition to our main estimates of deaths attributable to ambient $PM_{2.5}$ air pollution on the island of Ireland, we also estimate attributable deaths under a number of change scenarios where air pollution data are replaced by hypothetical levels of air pollution corresponding to different degrees of decrease/increase from 2019 pollution levels. The resulting figures reflect our best estimates of the number of premature deaths attributable to ambient $PM_{2.5}$ air pollution were long-term exposure to be at the level hypothesised in the scenario. Note that the full extent of any changes in attributable deaths implied by these scenarios would not occur immediately but would take place over a number of years. However, COMEAP [22] suggests the majority of changes in mortality risk would likely occur within five years.

Local-level Fine Particulate Matter Pollution on the Island of Ireland

Figure 1 shows area-level average ambient $PM_{2.5}$ air pollution levels across the island of Ireland in 2019 (and Table 1 reports the figures). As we might expect, pollution exposure was generally highest in more densely populated areas, with Belfast (10.1 µg/m^3) and Limerick City (11.1 µg/m^3) experiencing the highest levels of pollution in NI and ROI, respectively, closely followed by other urban centres including Waterford City and Dublin City. Generally, the west of the island was the least polluted, with Fermanagh and Omagh (7.4 µg/m^3) in NI, and Mayo County (5.8 µg/m^3) in ROI, experiencing the lowest $PM_{2.5}$ levels in 2019. Note, however, that even in counties with low *average* levels of pollution, there can still be pollution hotspots where people are exposed to much higher pollution levels, e.g. Letterkenny and Donegal Town within Donegal County.

FIGURE 1. POPULATION WEIGHTED $PM_{2.5}$ LEVELS IN 2019



Although average $PM_{2.5}$ pollution exposures in all ROI counties and all NI LGDs met the relevant legal limits [30], [31], they everywhere exceeded the most recent (2021) WHO AQG level for $PM_{2.5}$ [19], above which there is compelling evidence for harm to human health.

Local-level Estimates of the Mortality Burden of Fine Particulate Matter on the Island of Ireland

We present our estimates of the mortality burdens of $PM_{2.5}$ exposure in 2019 by local area in NI and ROI, respectively, in Tables 1 and 2. In each table, columns 2 and 3 show deaths due to all causes (minus deaths due to external causes) and due to circulatory-related diseases; column 4 shows the estimated $PM_{2.5}$ level in each local area in 2019; columns 5-6 show the percentage of deaths attributable to ambient $PM_{2.5}$ air pollution, i.e. the AFs. The final two columns provide the estimated number of attributable deaths by cause.

Overall, the table suggests that 936 and 1,682 all-cause deaths are attributable to exposure to $PM_{2.5}$ in NI and ROI respectively, while the number of attributable circulatory-related deaths are 314 and 681 in NI and ROI respectively. In total, across the island of Ireland, 2,618 all-cause deaths including 995 circulatory-related deaths are attributable to long-term exposure to $PM_{2.5}$ in 2019. Given their relatively high pollution levels and large populations, it is no surprise that Dublin City and Belfast have the largest estimated number of attributable all-cause (circulatory) deaths: 270 (103) for Dublin and 216 (66) for Belfast. Note, however, that all counties in ROI and all LGDs in NI suffer premature deaths attributable to ambient $PM_{2.5}$ air pollution.

As with any such estimates there are important caveats to bear in mind here. These estimates were generated using analytical methods underpinned by a number of assumptions and data which are subject to some uncertainty. This means there is some uncertainty surrounding the figures, which in the case of the mortality burden calculations should be seen as representing 'central' estimates within a range of possible values, which could vary depending on which methods, data or assumptions are employed. A brief discussion of this, drawing on the discussion in PHE [14], is presented in Appendix 2.

TABLE 1. ESTIMATED MORTALITY BURDEN in NI 2019							
	Deaths (16+)	**Deaths (16+)**	**$PM_{2.5}$ µg/m³**	**Attributable Fraction**		**Attributable Deaths due to $PM_{2.5}$ Air Pollution**	
Area	**All-cause**	**Circulatory**		**All-cause**	**Circulatory**	**All-cause**	**Circulatory**
Antrim and Newtownabbey	1,123	273	9.4	7.0%	9.4%	79	26
Ards and North Down	1,414	338	8.9	6.6%	8.8%	93	30
Armagh City, Banbridge and Craigavon	1,402	364	8.7	6.5%	8.6%	90	31
Belfast	2,891	664	10.1	7.5%	10.0%	216	66
Causeway Coast and Glens	1,182	323	7.5	5.6%	7.5%	66	24
Derry City and Strabane	1,164	278	8.4	6.2%	8.4%	73	23
Fermanagh and Omagh	883	215	7.4	5.5%	7.4%	49	16
Lisburn and Castlereagh	1,149	285	9.3	6.9%	9.2%	79	26
Mid and East Antrim	1,213	317	8.5	6.3%	8.5%	77	27
Mid Ulster	958	280	8.1	6.0%	8.1%	58	23
Newry, Mourne and Down	1,319	345	8.0	5.9%	8.0%	78	27
NI	**14,698**	**3,682**	**8.6**	**6.4%**	**8.5%**	**936**	**314**

Note. The national-level estimates presented here are generated directly from applying the methods described in Appendix 2 at the national level. An alternative way to produce a national estimate is to add up the local estimates; applying this approach would generate a national estimate of 958 all-cause ADs and 320 cardiovascular ADs.

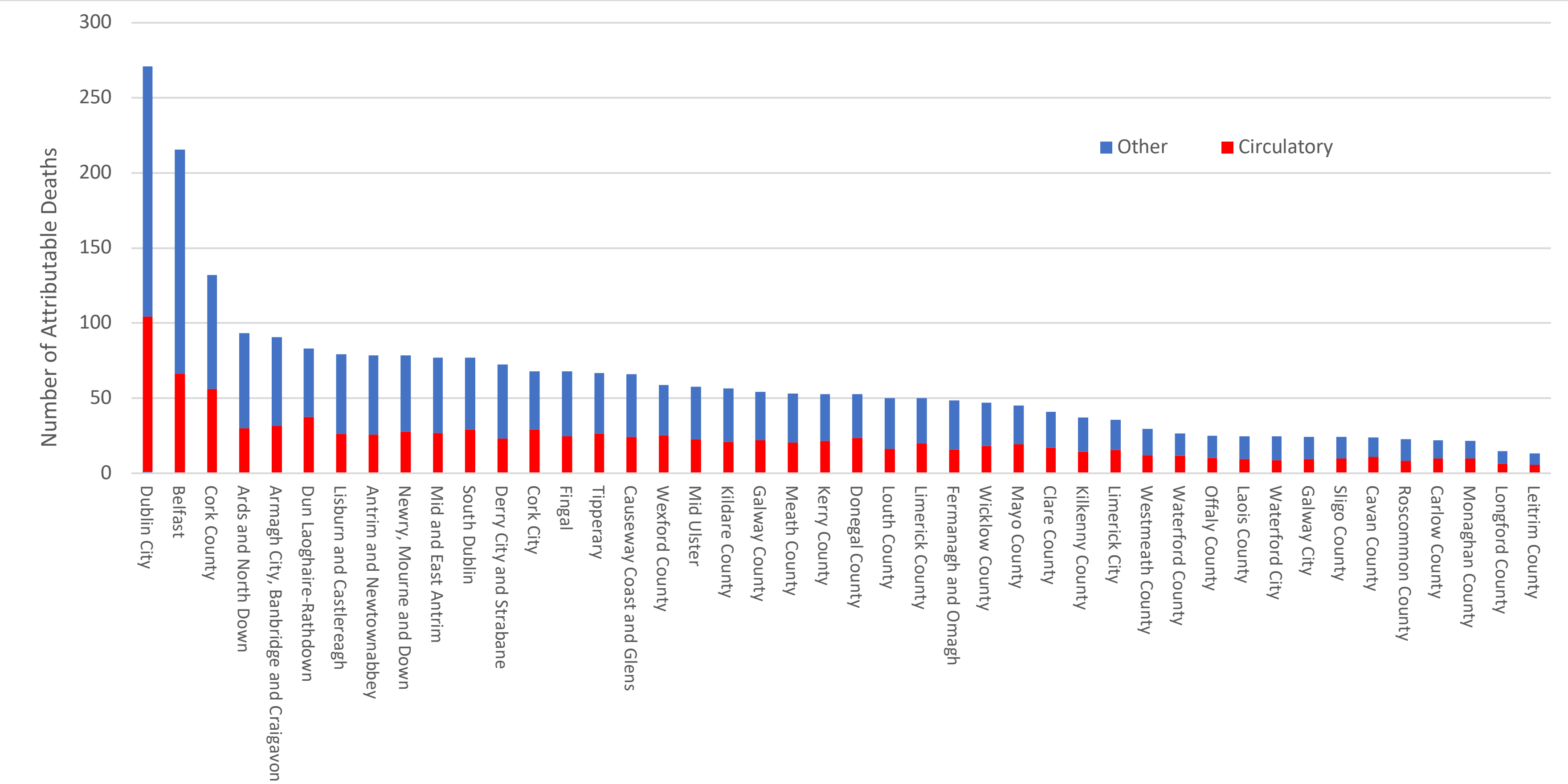
TABLE 2. ESTIMATED MORTALITY BURDEN in ROI 2019							
	Deaths (15+)	**Deaths (all ages)**	**$PM_{2.5}$ µg/m³**	**Attributable Fraction**		**Attributable Deaths due to $PM_{2.5}$ Air Pollution**	
Area	**All-cause**	**Circulatory**		**All-cause**	**Circulatory**	**All-cause**	**Circulatory**
Carlow County	375	125	7.8	5.8%	7.8%	22	10
Cavan County	453	153	7.0	5.3%	7.1%	24	11
Clare County	744	227	7.4	5.5%	7.4%	41	17
Cork City	1,029	331	8.9	6.6%	8.8%	68	29
Cork County	2,422	768	7.3	5.5%	7.3%	132	56
Donegal County	1,168	385	6.0	4.5%	6.1%	53	23
Dublin City	4,024	1,148	9.0	6.7%	9.0%	270	103
Dún Laoghaire-Rathdown	1,422	478	7.8	5.8%	7.8%	83	38
Fingal	1,055	284	8.6	6.4%	8.6%	68	24
Galway City	375	109	8.7	6.5%	8.7%	24	9
Galway County	1,213	366	5.9	4.5%	6.0%	54	22
Kerry County	1,159	351	6.0	4.5%	6.1%	53	21
Kildare County	968	266	7.8	5.8%	7.8%	56	21
Kilkenny County	624	181	7.9	5.9%	8.0%	37	14
Laois County	433	122	7.6	5.7%	7.6%	24	9
Leitrim County	287	90	6.2	4.6%	6.2%	13	6
Limerick City	437	142	11.1	8.2%	10.9%	36	16
Limerick County	883	265	7.6	5.7%	7.6%	50	20
Longford County	284	94	6.9	5.2%	6.9%	15	7
Louth County	798	194	8.4	6.3%	8.4%	50	16
Mayo County	1,040	334	5.8	4.3%	5.8%	45	19
Meath County	884	255	8.0	6.0%	8.0%	53	21

Monaghan County	399	136	7.2	5.4%	7.3%	22	10
Offaly County	462	142	7.2	5.4%	7.2%	25	10
Roscommo n County	490	135	6.2	4.7%	6.3%	23	8
Sligo County	497	152	6.5	4.9%	6.6%	24	10
South Dublin	1,260	355	8.2	6.1%	8.2%	77	29
Tipperary	1,213	357	7.3	5.5%	7.4%	67	26
Waterford City	315	85	10.5	7.8%	10.4%	24	9
Waterford County	463	152	7.6	5.7%	7.6%	26	12
Westmeath County	535	164	7.4	5.5%	7.4%	30	12
Wexford County	1,027	329	7.6	5.7%	7.7%	59	25
Wicklow County	874	253	7.2	5.4%	7.2%	47	18
ROI	**29,612**	**8,928**	**7.6**	**5.7%**	**7.6%**	**1,682**	**681**

Note. The national-level estimates presented here are generated directly from applying the methods described in Appendix 2 at the national level. An alternative way to produce a national estimate is to add up the local estimates; applying this approach would generate a national estimate of 1,695 all-cause ADs and 683 cardiovascular ADs.

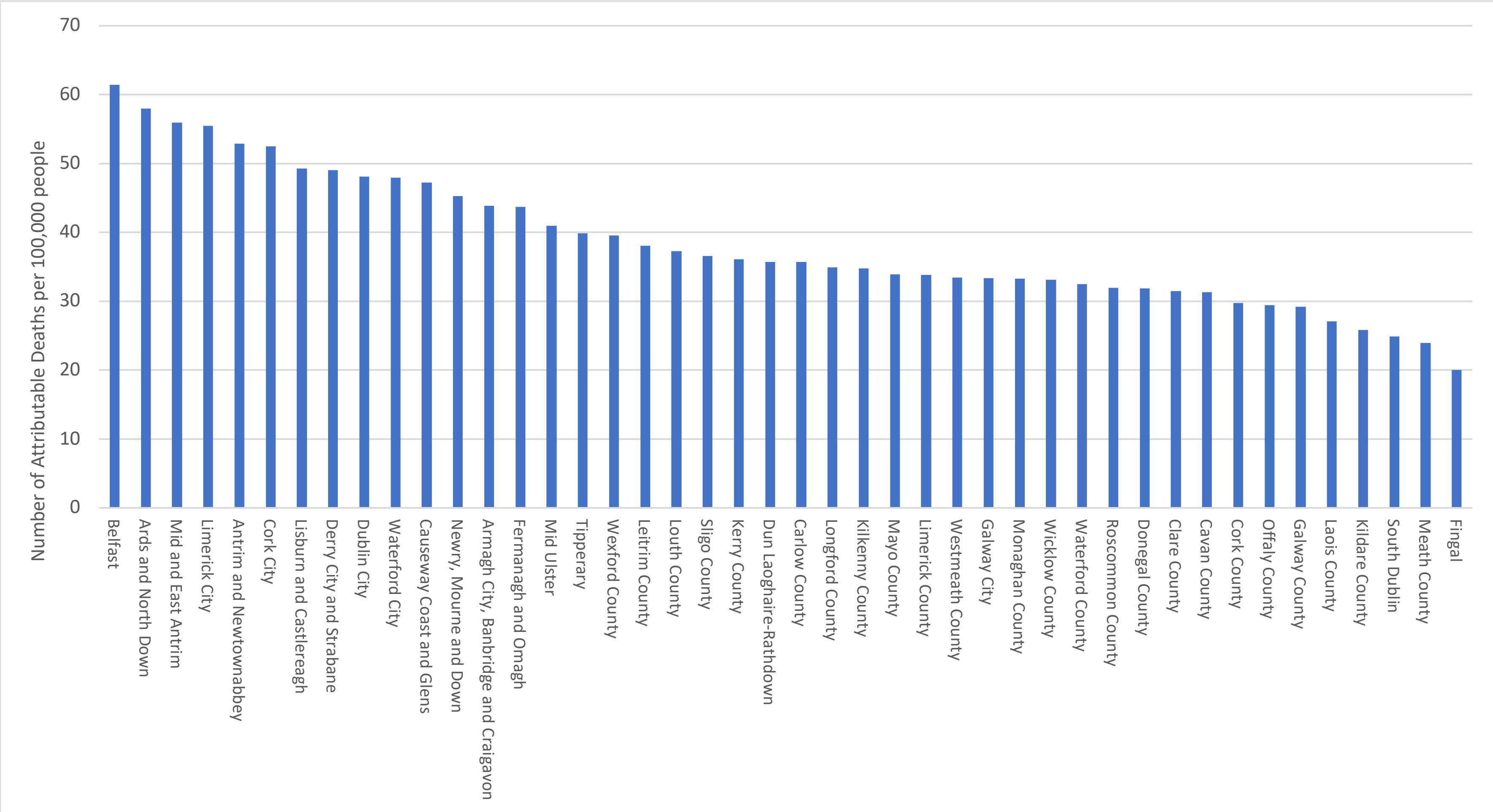
Figure 2 shows the number of attributable all-cause and circulatory deaths in each county/LGD in graphical form, with local areas sorted by the number of all-cause attributable deaths. Because the number of attributable deaths in each area in part reflects the population size of each area, Figure 3 similarly presents attributable all-cause deaths per 100,000 population. Note that our estimates suggest that Belfast has the highest rate of attributable deaths by population on the island of Ireland, with Dublin falling a little further down the distribution. Also note that all three of the local areas with the highest rates of estimated attributable deaths by population are in NI, with the next highest being Limerick City, which has the highest rate within ROI.

FIGURE 2: ESTIMATED MORTALITY BURDEN, ISLAND OF IRELAND, BY COUNTY/LGD, 2019



Note. The bar chart shows the estimated number of deaths attributable to $PM_{2.5}$ by local area, where each bar is composed of circulatory-related plus non-circulatory attributable deaths.

FIGURE 3: ESTIMATED MORTALITY BURDEN PER 100,000 POPULATION, ISLAND OF IRELAND, BY COUNTY/LGD, 2019



Note. Unlike the mortality estimates, the population data used here (sourced from EEA at the 1km grid-square level), are not restricted by age, so include those <16 in NI and <15 in ROI.

Estimated Changes in the Mortality Burden under Hypothetical Scenarios with Higher/Lower Pollution Levels

If we are able to reduce ambient $PM_{2.5}$ air pollution levels on the island of Ireland then, over time, we can reduce the number of attributable deaths associated with air pollution. In this section, we present three hypothetical $PM_{2.5}$-reduction scenarios and re-estimate the number of deaths attributable to long-term exposure to ambient $PM_{2.5}$ air pollution in each case. In contrast, if levels of ambient $PM_{2.5}$ air pollution *increase*, e.g. if the dramatic recent increases in the price of natural gas lead to increased solid fuel burning, then we would expect higher pollution levels and an increase in the number of attributable deaths, other things being equal. We present one such $PM_{2.5}$-increase scenario here.

The following scenarios are considered, with estimated attributable deaths in each case, at the country level, presented in Table 3:

1. 20% lower $PM_{2.5}$ level in all local areas
2. 50% lower $PM_{2.5}$ level in all local areas
3. $PM_{2.5}$ level equal to the WHO 2021 AQG level of 5 $\mu g/m^3$ in all local areas
4. 20% higher $PM_{2.5}$ level in all local areas

Although the full extent of any changes in mortality implied by these scenarios would take several years to be realised, over time each of the $PM_{2.5}$-reduction scenarios would lead to a fall in the annual number of attributable deaths, other things being equal. Under scenarios 1 and 2, our long-run (i.e. full extent) estimates of the number of lives potentially saved each year across the island of Ireland are 511 and 1,289, respectively. Under scenario 4 – a 20% increase in $PM_{2.5}$ levels – we estimate that the number of deaths attributable to ambient $PM_{2.5}$ pollution across the island of Ireland would potentially increase, over time, by 505 deaths per year. Table A1 in the Appendix gives the equivalent figures at the county and LGD level for ROI and NI, respectively.

Scenario 3 is perhaps the most interesting from a policy perspective, given it implies different degrees of $PM_{2.5}$ pollution reduction in different areas, and given recent calls for pollution regulations to reflect WHO AQG levels more closely [32]. Under scenario 3, our long-run estimate of the number of lives potentially saved each year across the island of Ireland is 946, with 382 in NI and 564 in ROI. Again, Table A1 in the Appendix gives the equivalent figures at the county and LGD level. For example, our estimates suggest that cutting ambient $PM_{2.5}$ air pollution to the 2021 WHO AQG level in Belfast and

Dublin would, in the long run, potentially save more than 100 lives in each city each year. Figure A1 in the Appendix presents these county/LGD level estimates in graphical form.

Ambient $PM_{2.5}$ air pollution on the island of Ireland has in fact been falling slowly over the last decade [33], and in some rural areas was already close to the 2021 WHO AQG level in 2019. In the absence of further policy intervention, however, it seems highly unlikely that WHO AQG levels would be reached in many parts of ROI and NI over any reasonable timeframe. At the country level, for example, a naïve extrapolation of current trends – likely to exaggerate the speed with which pollution levels will fall absent further intervention, particularly given the current fuel price crisis – would suggest such levels would not be reached until 2035 (ROI) and 2040 (NI), respectively. Getting there faster could potentially save many lives.

TABLE 3: HYPOTHETICAL SCENARIOS FOLLOWING CHANGES IN $PM_{2.5}$

Countries	Hypothetical $PM_{2.5}$ ($\mu g/m^3$)	Estimated attributable deaths associated with hypothetical $PM_{2.5}$ level	Difference between hypothetical and 2019 estimated number of attributable deaths
Scenario 1: REDUCTION in the level of $PM_{2.5}$ by 20%			
NI	6.8	754	-182
ROI	6.1	1,354	-329
All Ireland		2,108	-511
Scenario 2: REDUCTION in the level of $PM_{2.5}$ by 50%			
NI	4.3	476	-460
ROI	3.8	853	-829
All Ireland		1,329	-1,289
Scenario 3: REDUCTION in $PM_{2.5}$ level to WHO 2021 AQG Level			
NI	5.0	555	-382
ROI	5.0	1,118	-564
All Ireland		1,673	-946
Scenario 4: INCREASE in the level of $PM_{2.5}$ by 20%			
NI	10.3	1,116	+180
ROI	9.1	2,007	+325
All Ireland		3,123	+505

Discussion: What These Estimates Tell Us and Implications for Policy

This report estimates that exposure to ambient $PM_{2.5}$ led to just over 2,600 premature deaths on the island of Ireland in 2019, with approximately 900 in NI and approximately 1,700 in ROI. We also estimate that almost 1,000 of these estimated attributable deaths are circulatory-related. Following a simple approximation which assumes a loss of 12 life-years per attributable premature death, following PHE [14], our overall estimate (2,618 deaths) corresponds to approximately 31,500 life-years lost across NI and ROI each year. Further, although we show that ambient air pollution is associated with premature deaths everywhere across NI and ROI, we show that the problem is most acute in major urban centres where pollution levels, and populations, are highest.

We then show how plausibly achievable reductions in air pollution, e.g. a cut of 20% over 2019 levels, could potentially save hundreds of lives each year. For example, we estimate that a 20% cut in $PM_{2.5}$ exposures relative to 2019 levels has the potential to save just over 500 lives per year across the island of Ireland. (The opposite is the case if we allow pollution exposures to increase by 20% relative to 2019 levels.) If both ROI and NI committed to reducing $PM_{2.5}$ levels to those suggested in the current WHO AQGs, our estimates suggest this has the potential to save almost 1,000 lives per year.

Although these are the first such estimates to cover both NI and ROI at the local level, and the first to do so for 2019, there are earlier estimates of the mortality burden of ambient $PM_{2.5}$ in ROI and NI to which we can compare our own estimates. For example, the EEA estimates that there are 1,300 premature deaths per year due to $PM_{2.5}$ air pollution in ROI [13]. Similarly, the British Heart Foundation estimates that there are 800 premature deaths per year due to air pollution in NI [34]. These are slightly lower than our own estimates, in part reflecting our adoption of a higher RR estimate (1.08 compared to 1.06) following recent recommendations [22]. At the local level, PHE [14] presents estimated deaths due to anthropogenic $PM_{2.5}$ exposure across NI in 2010. The local level pattern is similar to that presented here, with the highest number of attributable deaths in Belfast. The PHE estimate of attributable deaths for NI as a whole – at 553 – is also somewhat lower than our estimate here, again reflecting use of a lower RR estimate, but also their restriction to deaths in the population aged 25+ years only and to anthropogenic $PM_{2.5}$ only. Note that all these estimates come with uncertainty, so are best thought of as the mid-points of an estimated range of premature deaths associated with $PM_{2.5}$ pollution. Our estimates, which are similarly subject to uncertainty, fall at the upper ends of these existing estimated ranges. Our estimates for ROI and NI are also higher than the nearest equivalent estimates presented as part of the 2019 Global Burden of Disease Study (535 and 316 respectively), which primarily reflects additional methodological differences [35].

There is a great deal of policy interest in NI concerning the health impacts of air pollution, e.g. consider recent consultations on a draft Environment Strategy for Northern Ireland [36] and the Clean Air Strategy Discussion Document [8]. Despite this, however, potential policy interventions that could save lives in NI are, at the time of writing, held back by ongoing delays to forming a new NI Executive. While these delays continue, we still have no Clean Air Strategy for Northern Ireland.

While NI delays, policy progresses elsewhere in the UK, including under Clean Air Strategies published by each of the other UK nations. For example, in May 2021, England introduced restrictions on the sale of wet wood for domestic burning, limits on the emission of sulphur and smoke from manufactured solid fuels, and began to phase out the sale of bituminous coal. From January 2022, only Ecodesign compliant wood stoves can enter the market for sale in England. The Welsh Government is also considering a ban on bituminous coal commencing 2024/25 and the Scottish Government has similarly set out a series of actions to tackle emissions from domestic fuel burning, according to the Draft UK National Air Pollution Control Programme (NAPCP) [37]. This consultation states that while the NI Government is also considering potential restrictions on domestic solid fuel burning, "policy development regarding the restrictions on the types of solid fuels burnt in domestic combustion in Northern Ireland is at an early stage, with the exact date for adoption and types of fuels that restrictions will apply to subject to further analysis and consultation." [37, p. 13].

Among other things, the Draft UK NAPCP includes a number of potential policy interventions that are under consideration but are not yet firm government policy, and estimates of how they might impact on emissions of $PM_{2.5}$ and other pollutants. These include further restrictions on the domestic burning of solid fuels, information campaigns to raise awareness, and various road transport policies with potential to impact on pollution. Taken together, at the upper end of projected impacts, these interventions have the potential to reduce $PM_{2.5}$ levels by close to 20% on projected 2030 levels in the absence of further intervention. Were these policies introduced in NI, and were these upper-end projections realised, our estimates suggest that they could save almost 200 lives per year in NI.

Policy in relation to air pollution is also evolving in the ROI. For example, following the success of previous local bans on smoky coal, from 31st October 2022 the Government in the ROI have extended the smoky coal ban nationally [7]. A key aspect of the ban is that it targets the *supply* of smoky fuels, making it easier to enforce than restrictions on the *use* of smoky fuels. If you cannot buy smoky fuels you cannot use them. This contrasts with the Smoke Control Area approach used in NI where smoky fuels could still be purchased even though their use was restricted.

Another welcome development in the ROI is the recent extension of the air pollution monitoring network [38]. For governments to make informed policy decisions about what works, when and for whom, and if they are to target non-universal interventions where they are most needed, then such monitoring is essential. But there are still important gaps in the ROI monitoring network, including for smaller towns (for a map, as of 2020, see [38, p. 20]). There are also substantial gaps in the $PM_{2.5}$ monitoring network in NI (for a 'live' map see the Air Quality NI website [39]).

There is much more that could be done in both jurisdictions, including but not limited to further efforts to improve energy efficiency particularly in older houses, improvements to public transport networks and further incentives to use them in place of private cars, and further extending regulatory restrictions and/or imposing additional taxes on the most polluting fuels. The WHO AQGs could be written into law as binding regulatory thresholds. There have already been calls to take this step, for example from the ROI Environmental Protection Agency [40], albeit in relation to the previous *higher* WHO AQG for $PM_{2.5}$ of 10 $\mu g/m^3$. Scotland was the first country in Europe to adopt the previous WHO AQG for $PM_{2.5}$ into domestic legislation, with local authorities obliged to take action where the AQG level is exceeded [41]. A similar approach in the ROI and NI is possible, e.g. with the previous WHO AQG of 10 $\mu g/m^3$ treated as an interim threshold on the way to meeting the new WHO AQG of 5 $\mu g/m^3$ in the longer term.

Air pollution does not respect borders, so reducing air pollution across the island is likely to require collaboration between the governments in NI and ROI, and lack of policy coordination may make some interventions unilaterally introduced in one jurisdiction less effective than they might otherwise be. For example, if smoky coal is still available to purchase in NI, then the recent extension to the smoky coal ban in the ROI may fall short of its potential impacts on $PM_{2.5}$ pollution, particularly in border counties. There is potential to gain from both cross-border conversation and cross-border cooperation in this area, ranging from regular North-South Ministerial meetings on air pollution, through to bilateral interventions and regulatory alignment in both jurisdictions. Cross-border co-operation on air pollution might also be supported by an expert committee on the island comprising of the leading experts in the area of air quality and public health in ROI and NI, building on the success of COMEAP in the UK, and perhaps in collaboration with both COMEAP and the Institute of Public Health, which could advise policy makers as new research evidence becomes available.

It is important at this point to restate that we recognise that efforts to further reduce air pollution on the island of Ireland will invariably involve trade-offs. In principle, however, it should be possible to implement transitional allowances to help compensate for extra costs borne by those who would otherwise lose out from additional regulations, e.g. on solid fuel burning for domestic heating. In contrast, the cost of doing nothing, even if air pollution continues its current slowly declining trajectory, is likely to be many thousands of additional deaths over the coming years.

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Appendix 1: Additional Estimates

Table A1. Hypothetical Scenarios following changes in $PM_{2.5}$ by local area

	Scenario 1: 20% Reduction in $PM_{2.5}$ level		Scenario 2: 50% Reduction in $PM_{2.5}$ level		Scenario 3: Reduction in $PM_{2.5}$ level to WHO 2021 AQGL		Scenario 4: 20% Increases in $PM_{2.5}$ level	
	$PM_{2.5}$	Reduction in AAC*	$PM_{2.5}$	Reduction in AAC	$PM_{2.5}$	Reduction in AAC	$PM_{2.5}$	Increases in AAC
Northern Ireland								
Antrim and Newtownabbey	7.5	-15	4.7	-39	5	-36	11.3	15
Ards and North Down	7.1	-18	4.4	-46	5	-40	10.6	18
Armagh City, Banbridge and Craigavon	6.9	-18	4.3	-44	5	-38	10.4	17
Belfast	8.1	-42	5.0	-106	5	-107	12.1	41
Causeway Coast and Glens	6.0	-13	3.7	-33	5	-21	9.0	13
Derry City and Strabane	6.7	-14	4.2	-36	5	-29	10.0	14
Fermanagh and Omagh	5.9	-10	3.7	-24	5	-15	8.8	9
Lisburn and Castlereagh	7.4	-15	4.6	-39	5	-36	11.1	15
Mid and East Antrim	6.8	-15	4.3	-38	5	-31	10.2	15

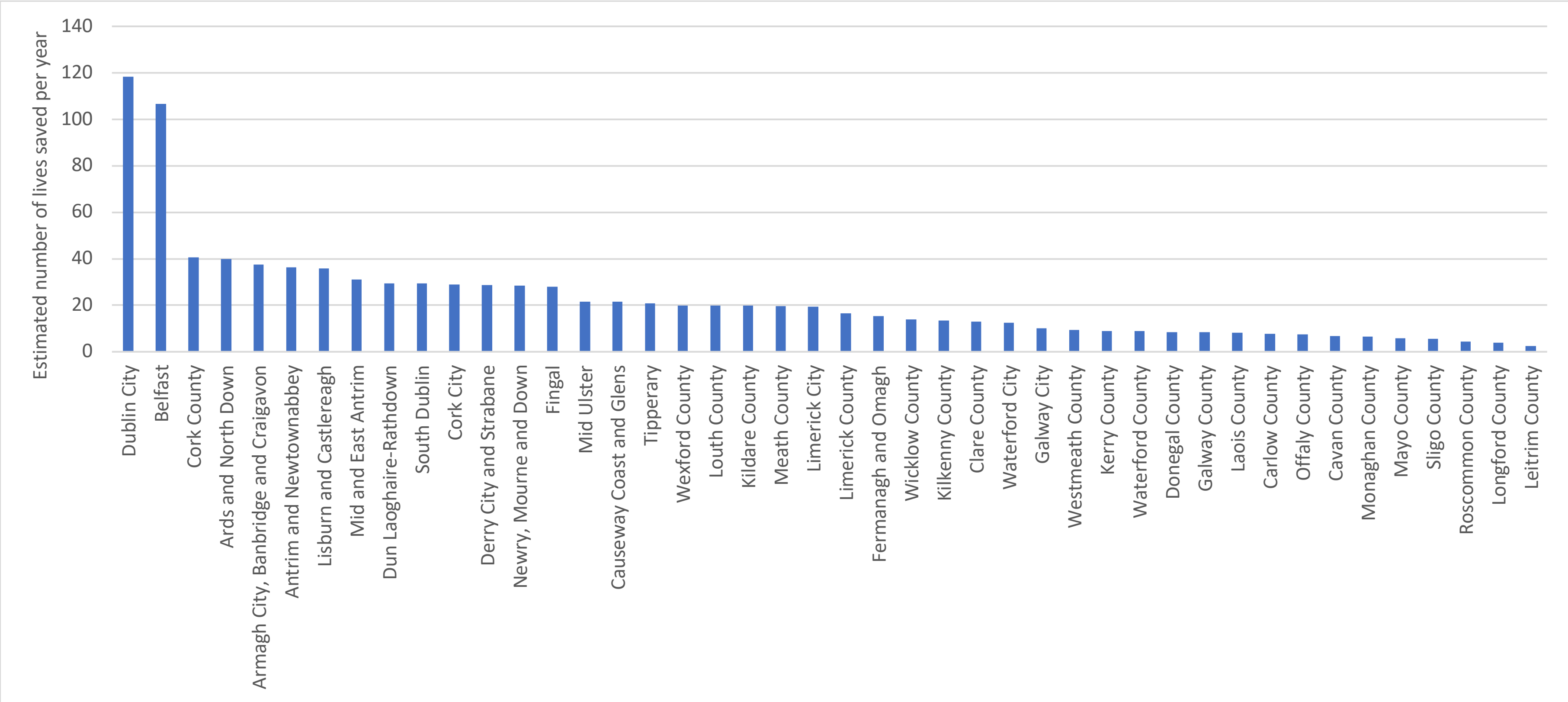
Mid Ulster	6.5	-11	4.0	-28	5	-22	9.7	11
Newry, Mourne and Down	6.4	-15	4.0	-39	5	-29	9.5	15
Total of NI LGDs		-186		-471		-403	10.3	184
Republic of Ireland								
Carlow County	6.3	-4	3.9	-11	5	-8	9.4	4
Cavan County	5.6	-5	3.5	-12	5	-7	8.5	5
Clare County	5.9	-8	3.7	-20	5	-13	8.9	8
Cork City	7.1	-13	4.4	-33	5	-29	10.6	13
Cork County	5.8	-26	3.6	-65	5	-41	8.7	26
Donegal County	4.8	-10	3.0	-26	5	-9	7.2	10
Dublin City	7.2	-53	4.5	-133	5	-118	10.8	52
Dún Laoghaire-Rathdown	6.3	-16	3.9	-41	5	-29	9.4	16
Fingal	6.9	-13	4.3	-33	5	-28	10.4	13
Galway City	7.0	-5	4.4	-12	5	-10	10.5	5
Galway County	4.7	-11	3.0	-27	5	-8	7.1	11
Kerry County	4.8	-10	3.0	-26	5	-9	7.3	10

Kildare County	6.2	-11	3.9	-28	5	-20	9.4	11
Kilkenny County	6.4	-7	4.0	-18	5	-13	9.5	7
Laois County	6.1	-5	3.8	-12	5	-8	9.1	5
Leitrim County	4.9	-3	3.1	-7	5	-2	7.4	3
Limerick City	8.9	-7	5.6	-18	5	-19	13.3	7
Limerick County	6.1	-10	3.8	-25	5	-17	9.1	10
Longford County	5.5	-3	3.4	-7	5	-4	8.3	3
Louth County	6.7	-10	4.2	-25	5	-20	10.1	10
Mayo County	4.6	-9	2.9	-22	5	-6	6.9	9
Meath County	6.4	-10	4.0	-26	5	-20	9.6	10
Monaghan County	5.8	-4	3.6	-11	5	-7	8.7	4
Offaly County	5.7	-5	3.6	-12	5	-7	8.6	5
Roscommon County	5.0	-4	3.1	-11	5	-4	7.4	4
Sligo County	5.2	-5	3.2	-12	5	-5	7.8	5
South Dublin	6.5	-15	4.1	-38	5	-29	9.8	15
Tipperary	5.9	-13	3.7	-33	5	-21	8.8	13
Waterford City	8.4	-5	5.2	-12	5	-13	12.6	5
Waterford County	6.1	-5	3.8	-13	5	-9	9.1	5
Westmeath County	5.9	-6	3.7	-15	5	-9	8.9	6

Wexford County	6.1	-11	3.8	-29	5	-20	9.2	11
Wicklow County	5.7	-9	3.6	-23	5	-14	8.6	9
Total of ROI counties		-331		-835		-577	9.1	327
All		-517		-1,305		-980		511

AAC = All Attributed Cause of Death.

FIGURE A1: ESTIMATED LIVES SAVED UNDER SCENARIO 3 (CUTTING $PM_{2.5}$ LEVELS TO WHO 2021 AQG) BY AREA



Appendix 2: Further Details on Data Sources and Methods

This appendix describes the methodology used to calculate the mortality burden of ambient $PM_{2.5}$ air pollution in this report. The calculations involve three key inputs: (i) area-level population-weighted $PM_{2.5}$ levels, (ii) area-level counts of the annual number of deaths, and (iii) a numerical value governing the relationship between $PM_{2.5}$ exposure and the risk of mortality. The mortality calculations follow the approach and recommendations on quantifying the mortality burden of long-term exposure to ambient $PM_{2.5}$ air pollution set out in and PHE [14] and COMEAP [20]–[22] and were performed using data from several sources.

Step 1: Calculating population-weighted area-level $PM_{2.5}$ levels

The first step was to generate estimates of the annual average outdoor $PM_{2.5}$ level in 2019 for each LGD in NI and county in the ROI. Estimates at this geographical level are not readily available and thus had to be produced by the report authors. This was achieved by aggregating grid square-level pollution data using the method set out in PHE [14].

The grid square pollution data used in this report were produced by the EEA [24]. The key advantage of this data source is that it offers all-Ireland pollution data generated in a way that is consistent across countries. Harmonisation across the island or Ireland is important to ensure that results are not affected by differences in how pollution levels are modelled. Alternative sources of pollution data were considered but disregarded. For example, comparable data published by the Department for Environment, Food & Rural Affairs (DEFRA) was only available for NI [42], while a full-scale modelling exercise by the report authors using monitoring station data was beyond the scope of this report.

The EEA publishes annual average ambient $PM_{2.5}$ concentration maps for most European countries, including NI and the ROI. Their mapping method combines monitoring data with the results from a chemical transport model and other supplementary data (such as land cover, meteorological and satellite data). Further information about the modelling process can be found in EEA [24]. The data are available for download as 1x1 km grid square shapefiles containing (among other information) annual average $PM_{2.5}$ concentrations and population counts. All data processing described in this section was performed on the 2019 shapefiles using *Quantum Geographical Information Systems* software [43].

The following steps were taken to calculate population-weighted $PM_{2.5}$ levels by area. First, the grid squares located within the boundaries of the island of Ireland were isolated (necessary because the pollution shapefile contains data for the whole of Europe). These grid squares were then allocated to counties and LGDs. Next, for each grid square, the concentration value was multiplied by the population count, and this product summed over grid squares within each area; this yields the numerator in (1) below, one for each area. The denominator for (1) was generated by summing the population over grid squares within each area. For each area, dividing the former by the latter yields its population-weighted $PM_{2.5}$ level. Consider area *A,* for example. Assuming it contains *G* grid squares, the relevant formula is:

$$\frac{\sum_{g=1}^{G}(POPULATION_g \times CONCENTRATION_g)}{\sum_{g=1}^{G} POPULATION_g} \quad (1)$$

An area's population-weighted concentration takes into account not only the level of pollution within that area but also the degree of human exposure. This is what we map in Figure 1 – the map of $PM_{2.5}$ pollution exposures on the island of Ireland – in the main text. Note that this is a measure of the *total* $PM_{2.5}$ concentration, inclusive of both anthropogenic and non-anthropogenic sources.

Step 2: Mortality data

The second key input is a measure of mortality in each area in 2019. For ROI, counts of the number of deaths, disaggregated by age group, cause of death and area, were obtained from the CSO [27]–[29]. For NI, the corresponding data were obtained from NISRA [25], [26]. The underlying cause of death (the disease or injury which initiated the train of morbid events leading directly to death, or the circumstances of the accident or violence which produced the fatal injury) in both countries was reported using the ICD 10th Revision codes.

The mortality data were selected to be as consistent as possible across jurisdictions. When calculating the all-cause mortality burden, deaths due to external causes (e.g. accidents or injury) were removed as such deaths cannot be attributed to air pollution exposure; this subtraction was applied consistently in both countries using ICD-10 codes V01-Y98. However, there are some discrepancies in how deaths by cause are reported across countries which should be highlighted. As shown below, these differences affect only a small number of deaths and are therefore not expected to have a significant impact on the results.

First, when calculating the all-cause mortality burden, deaths at ages 15 and older in ROI, and 16 and older in NI, are used, owing to the degree of age disaggregation available in each country. Second, there is a minor discrepancy in the ICD-10 codes used to classify deaths due to circulatory diseases, with ROI using I00-I99 and NI using I00-I97 for circulatory diseases. Because there are very few deaths classified under I95-I99 'Other and unspecified disorders of the circulatory system', this discrepancy[1] has no significant impact. Third, in ROI, cause-specific deaths at the area level are only available for all ages, unlike in NI, where they are available for ages 16 and older. Again, because there are very few deaths caused by circulatory diseases[2] in young people, this does not significantly affect the results.

Step 3: Calculating the mortality burden of long-term $PM_{2.5}$ exposure

The mortality burden is defined here as the number of adult deaths (all-cause less external cause deaths, or circulatory deaths, where applicable) within each area that are attributable to long-term exposure to the local concentration of $PM_{2.5}$ air pollution, i.e. attributable deaths. The link between exposure levels and the additional risk of mortality is described by a concentration-response function. Previously, it was recommended that an additional 10 μg/m^3 increase in the $PM_{2.5}$ concentration increases the relative risk of mortality by 6%. However, COMEAP's recent update [22] recommends a value of 8% – the value used in this report. This updated figure is informed by a meta-analytic study [44] which analysed a more up-to-date set of epidemiological studies since the previous recommendations. The findings suggest that $PM_{2.5}$ exposure is more damaging for human health than previously thought, a judgement which is reflected in the updated WHO AQGs, which reduced the recommended guideline level for annual average $PM_{2.5}$ from 10 to 5 μg/m^3 [19]. The equivalent RR for circulatory-specific mortality is 11% [44].

The number of deaths attributed to $PM_{2.5}$ exposure is estimated by multiplying the attributable fraction (AF) by the overall number of deaths. The AF is a function of the relative risk value and is expressed as:

$$AF = 100 \times \frac{(RR-1)}{RR} \tag{2}$$

where RR denotes 'relative risk'.

To estimate the impact of the *local* concentration of $PM_{2.5}$ on mortality, the relative risk value needs to be scaled appropriately, since most areas on the island of Ireland have a $PM_{2.5}$ concentration different from 10 μg/m^3. Scaling is achieved using the following formula:

[1] According to Table 3.11, only 4 deaths in ROI were recorded under ICD-10 codes I95-I99 in 2019 (CSO 2021c).

[2] According to Table 3.11, only 5 circulatory deaths in ROI were recorded at ages 0-14 in 2019 (CSO 2021c).

$$RR = 1.08^{(x/10)} \tag{3}$$

where x denotes the population-weighted $PM_{2.5}$ concentration in the relevant area.

To illustrate how the number of attributable deaths is estimated, consider Dublin City, which in 2019 had an estimated $PM_{2.5}$ concentration of 9.0 µg/m^3 and experienced 4,024 adult deaths. Equation (3) implies an attributable fraction of 0.067 (or 6.7%):

$$AF = \frac{(1.07 - 1)}{1.07} = 0.067$$

where the scaled relative risk value (1.07) was determined using the formula:

$$RR = 1.08^{(9.0/10)} = 1.07$$

Multiplying the attributable fraction (0.067) by the number of adult deaths (4,024) yields our estimate of 270 adult all-cause deaths attributable to $PM_{2.5}$ exposure in Dublin City in 2019.

It is important to stress that this figure does not imply that 270 adult deaths were caused by $PM_{2.5}$ exposure in this year. Rather, it should be interpreted as indicating that local $PM_{2.5}$ exposure increased mortality risk in this local population to an amount equivalent to this number of deaths.

The Scenarios

To estimate attributable deaths under each hypothetical scenario described in this report we first replace the estimated pollution exposures in Step 1 above with the hypothetical level of pollution exposure in each area implied by the scenario. We then repeat steps 2 and 3 above. In each case we then give our estimate of the number of deaths likely associated with long-term exposure to $PM_{2.5}$ air pollution were $PM_{2.5}$ at the level implied by the scenario rather than the level actually experienced in 2019.

Note that the full extent of any changes in attributable deaths implied by these scenarios would not occur immediately but would take place over a number of years because of what is known as *cessation lag*, i.e. the time pattern of reductions in mortality hazards following a reduction in pollution [21]. COMEAP [21] assesses the available evidence on this as suggesting that although it could take up to

40 years for the full extent of changes in mortality risk under such scenarios to be realised, the majority of changes in mortality risk would likely be realised within five years.

Uncertainty

The results presented in this report are unavoidably subject to some uncertainties, which are noted here but described in more detail in PHE [14]. When interpreting the findings, these uncertainties should be borne in mind. All results should be seen as central estimates falling within a range of possible estimates, which could be different were different data used, different methods applied, or different assumptions made.

First, there is uncertainty about the true relative risk coefficients linking exposure to mortality risk; this cannot be known – only estimated – but we follow the latest COMEAP recommendations [22]. Second, relative risk coefficients have been derived from studies conducted in multiple other countries, which may have different relative risk profiles compared with ROI and NI, and these differences may be greater at the local level compared with the island level. Third, in some parts of the island, $PM_{2.5}$ concentrations may be lower than those observed in the studies reviewed in Chen and Hoek [44], while the mortality effects at these lower concentrations may be stronger or weaker. Fourth, area-level exposure is taken as a proxy for personal exposure, which will vary from resident to resident depending on patterns of behaviour. Fifth, the accuracy of modelled $PM_{2.5}$ concentration data depends on many factors, including the accuracy of input data and modelling techniques, uncertainty which again may be exacerbated at the local level.

List of Abbreviations

AF: attributable fraction

AQG: air quality guideline

COMEAP: Committee on the Medical Effects of Air Pollutants

CSO: Central Statistics Office (ROI)

DAERA: Department for Agriculture, Environment and Rural Affairs (NI)

DEFRA: Department for Environment, Food & Rural Affairs (UK)

EEA: European Environment Agency

EPA: Environmental Protection Agency (ROI)

EASAC: European Academic Science Advisory Council

GDP: gross domestic product

ICD: International Classification of Diseases

LGD: Local Government District (NI)

NI: Northern Ireland

NISRA: Northern Ireland Statistics and Research Agency

OECD: Organisation for Economic Co-operation and Development

PHE: Public Health England

$PM_{2.5}$: particulate matter, or particles, with a diameter of 2.5 micrometres or smaller

ROI: Republic of Ireland

RR: relative risk

WHO: World Health Organization

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