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Air pollution, deprivation and health: understanding relationships to add value to local air quality management policy and practice in Wales, UK

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ABSTRACT

Background Air pollution exposure reduces life expectancy. Air pollution, deprivation and poor-health status combinations can create increased and disproportionate disease burdens. Problems and solutions are rarely considered in a broad public health context, but doing so can add value to air quality management efforts by reducing air pollution risks, impacts and inequalities.

Methods An ecological study assessed small-area associations between air pollution (nitrogen dioxide and particulate matter), deprivation status and health outcomes in Wales, UK.

Results Air pollution concentrations were highest in 'most' deprived areas. When considered separately, deprivation-health associations were stronger than air pollution-health associations. Considered simultaneously, air pollution added to deprivation-health associations; interactions between air pollution and deprivation modified and strengthened associations with all-cause and respiratory disease mortality, especially in 'most' deprived areas where most-vulnerable people lived and where health needs were greatest.

Conclusion There is a need to reduce air pollution-related risks for all. However, it is also the case that greater health gains can result from considering local air pollution problems and solutions in the context of wider health-determinants and acting on a better understanding of relationships. Informed and co-ordinated air pollution mitigation and public health action in high deprivation and pollution areas can reduce risks and inequalities. To achieve this, greater public health integration and collaboration in local air quality management policy and practice is needed.

Keywords air pollution, deprivation, health, association, inequalities

Introduction

Exposure to air pollutants such as nitrogen dioxide (NO_2) and particulate matter (PM_{10} and $PM_{2.5}$) is linked with adverse health effects such as heart disease and stroke, respiratory disease and lung cancer.[1] On average, air pollution reduces the life expectancy of every resident in the United Kingdom (UK) by 7–8 months.[2] The health burden is substantial: 29 000 deaths and 307 000 lost life-years,[3] and 23 500 deaths and 277 000 lost life-years,[4] are attributed annually to $PM_{2.5}$ and NO_2 exposure, respectively in the UK.

While these headlines provide scope and profile to the UK air pollution-and-health problem, they mask important local-level variations in air pollution concentrations, exposures, risks and impacts. Air pollution concentrations (especially NO_2) vary across small geographies because they are influenced by local factors such as traffic, domestic, industrial and agricultural sources, as well as by more-distant sources and meteorological conditions. The differential exposure that results can interact with individual and

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population-level susceptibilities – 'intrinsic' (e.g. age, sex, genetics) and/or 'acquired' (e.g. income, education, housing, employment, service access, lifestyle/behaviour-related chronic illnesses)[5] – to influence health risks and impacts.[6] Thus, a *triple jeopardy* exists where air pollution, impaired health and deprivation can combine to create increased and disproportionate disease burdens between and within regions.[7,8]

Given these relationships, regarding local air pollution problems as isolated concerns is a mistake; they should be considered in the broadest possible public health context.[9] However, this is rarely recognized or realised. In the UK, the Local Air Quality Management (LAQM) regime provides the statutory framework to support collaborative action to assess and reduce local air pollution problems to protect health. Despite these intentions LAQM has historically failed to acknowledge the interaction between wider health determinants and air pollution, their influence on health risks and impacts, and how addressing these together may help solve problems.[10] As a consequence, LAQM and public health policy and practice have remained largely separate realms. This disconnect is detrimental; ill-informed decisions and ineffective or poorly-targeted actions taken based on a limited understanding of such relationships (or worse ignoring them altogether) can compound problems.[11]

Taking more-informed, targeted and co-ordinated action based on a good understanding of air pollution and health relationships could add value to existing LAQM arrangements and result in greater reductions in air pollution and population-level risks and inequalities. To test this hypothesis, and to inform the future development of LAQM-related policy and practice, this study assesses and quantifies associations between local-level air pollution and relevant health outcomes in the context of deprivation.

Methods

The setting for this ecological cross-sectional study was Wales, a UK principality with a population of 3.1 million people, localized air pollution problems resulting from mixed pollution sources,[12] and high levels of deprivation and health inequalities.[13] Wales was preferred for this study over other parts of the UK for three reasons. First, all 22 Welsh Local Authorities have equal status; since LAQM policy has been devolved from UK to Welsh Government its implementation through Local Authorities is consistent. Second, in contrast to other parts of the UK, the specialist public health function remains embedded in National Health Service structures. Third, new legislation – the Wellbeing of Future Generations (Wales) Act 2015 – places new statutory responsibilities on public bodies to collaborate to work sustainably to improve the social, economic, environmental and cultural well-being.[14] Unique to Wales, this new legislative framework offers opportunities to connect and enhance air quality management and public health policy and practice that do not exist elsewhere.

Given this study's emphasis on assessing local-level associations, data corresponded to Wales' smallest (highest resolution) administrative geographies called Lower-layer Super Output Areas (LSOA). These approximate 'neighbourhood' areas, of which there are 1909 in Wales, have an average 1600 residents (range: 1000–3000) and 650 households (range: 400–1200) and take into account proximity and social homogeneity.

The challenge of assessing air pollution exposure was overcome by using modelled data as these more-accurately reflect area-level exposure than the relatively crude use of measurements from monitors nearest to populations.[15] Modelled annual mean ambient NO_2, PM_{10} and $PM_{2.5}$ concentration data at 1 km^2-grid resolution were averaged for the 2011–2013 study period. These data were obtained from the UK Government's Pollution Climate Mapping model. This model generates validated annual estimates of area-level pollutant concentrations (based on 2011 as a baseline year, and projected annually) through land-use regression and kernel-based air dispersion modelling of known emission sources that takes account of meteorological conditions.[16] Prior to their use in this study, air pollution data were converted to population-weighted LSOA exposure estimates using standard methods.[17]

Records of all mortality (not only hospital deaths) for years 2011–2013 were obtained from Office for National Statistics through the NHS Wales Information Service. Numbers of deaths for health outcomes of interest in the context of air pollution exposure were identified by using appropriate International Classification of Diseases (ICD, version 10) codes. These were: all-cause non-accidental mortality (excluding injuries and external causes) (ICD-10: A00-R99), cardiovascular diseases (ICD-10: I00-I99), cerebrovascular diseases (ICD-10: I60-I69) and respiratory diseases (ICD-10: J00-J99). Mortality data for chronic liver disease (ICD10: K70, K73, K74) were also obtained to act as a 'control' outcome[18] since this outcome is known to be influenced by deprivation-related risk factors[19] but not by air pollution (noting emerging evidence from animal studies[20]). Hospital admissions data – records of all inpatient and day case activity undertaken in NHS Wales (morbidity) – were obtained from the Patient Episode Database for Wales for the same health outcomes, and for the same three-year study period. All 'health' data were then stratified by 5-year age

bands and linked to study-period-averaged mid-year LSOA population estimates obtained from the Office for National Statistics.[21]

Deprivation data were obtained from Welsh Government's Welsh Index of Multiple Deprivation (WIMD).[22] The WIMD assigns each LSOA in Wales a summary deprivation score derived from a weighted combination of data from eight domains: income (23.5%); employment (23.5%); health (14%); education (14%); geographical access to services (10%); community safety (5%); housing (5%) and physical environment (5%). Each of these domains includes several indicators of deprivation, e.g. income-deprivation is a composite measure reflecting the proportion of all residents of an LSOA with income below a defined level; it is calculated from LSOA numbers of income-related benefit claimants, tax credit recipients and supported asylum seekers. For this study, it was inappropriate to use the LSOA-level summary WIMD scores since their composition had been influenced by health and air pollution data. To avoid introducing bias from 'double-counting' these component data, income-deprivation domain data were used as an indicator of multiple deprivation.[18,23–25]

There were two phases of data analysis:

Linking and describing LSOA data

Each LSOA was assigned one of five income-deprivation status classifications. Quintiles were derived by ranking income-deprivation composite scores for all LSOAs and dividing the data into five roughly equal parts (each with 381 or 382 LSOAs and a population of approximately 600 000 people).

LSOAs were also assigned an air pollution status classification of being a 'low', 'moderately' or 'high' polluted area. Cut-off points for tertiles were determined by ordering the distribution of LSOA air pollution concentrations (for each pollutant) and dividing the data falling between the 5th and 95th percentile values into three equal parts. LSOAs with data values below the 5th percentile ($n = 40$ for NO_2, $n = 97$ for PM_{10}, $n = 90$ for $PM_{2.5}$) or above the 95th percentile ($n = 94$ for NO_2, $n = 90$ for PM_{10}, $n = 77$ for $PM_{2.5}$) were assigned either 'low' or 'high' polluted area status, as appropriate.

Area-level air pollution and income-deprivation status data, and mortality and hospital admissions data, were linked by LSOA using Microsoft Excel and ArcGIS 10.2.2 software. Linked data were subsequently aggregated based on deprivation and area-level NO_2, PM_{10} and $PM_{2.5}$ air pollution status. Using mortality and hospital admissions numerator data and mid-year population denominator estimates, European Age-Standardised Rates (EASR) with 95% confidence intervals (CI) were calculated for each health outcome.[26,27] Through this direct method of standardization, age-adjusted rates were derived by applying crude mortality or hospital admissions rates for each health outcome of interest (calculated post data aggregation) to a single reference population, in this case the European standard population. The result was standardised rates, adjusted for differences in the age structure of the population, which facilitated comparisons over time and place.

Assessing associations

Air pollution–health associations and, separately, *deprivation–health* associations, were assessed using rate ratios (RR) with 95% CI.[28,29] RRs compared rates of health outcomes in 'high' polluted or 'most' income-deprived areas with those in reference 'low' polluted or 'least' deprived areas. The a*ir pollution–deprivation–health* association assessment – which considered air pollution and deprivation interactions and their combined association with health outcomes – adopted the same method to compare the rates in reference 'low' polluted and 'least' deprived areas with elsewhere.

Results

Results are presented below for each data analysis phase.

Linking and describing LSOA data

Across all LSOAs, the annual mean NO_2 concentration was 17.7 $\mu g/m^3$ (5th percentile: 6.6 $\mu g/m^3$; 95th percentile: 36.7 $\mu g/m^3$), for PM_{10} it was 14.1 $\mu g/m^3$ (5th percentile: 11.4 $\mu g/m^3$; 95th percentile: 17.3 $\mu g/m^3$), and for $PM_{2.5}$ it was 9.5 $\mu g/m^3$ (5th percentile: 7.5 $\mu g/m^3$; 95th percentile: 11.8 $\mu g/m^3$). Local-level NO_2 concentrations varied substantially (Fig. 1). Concentrations were greatest over town and city agglomerations in south-east Wales, along main traffic routes such as the M4 motorway running between the south-east and mid-south Wales, and in heavily-industrialized areas like the busy sea port where several oil refineries are located in south-west Wales. Local-level PM10 and $PM_{2.5}$ concentrations also varied, but not to the same extent (not shown).

Income-deprivation status also varied at the local level (Fig. 1). The income-deprivation composite scores that lie under the LSOA classifications revealed that the proportion of people living in income deprivation ranged from 5% in some LSOAs to 31% in others (all-Wales average: 16%). Only 12% of 'most' deprived areas could be described as being rural compared with 27% of 'least' deprived areas; 'next least' deprived areas were least urbanized.

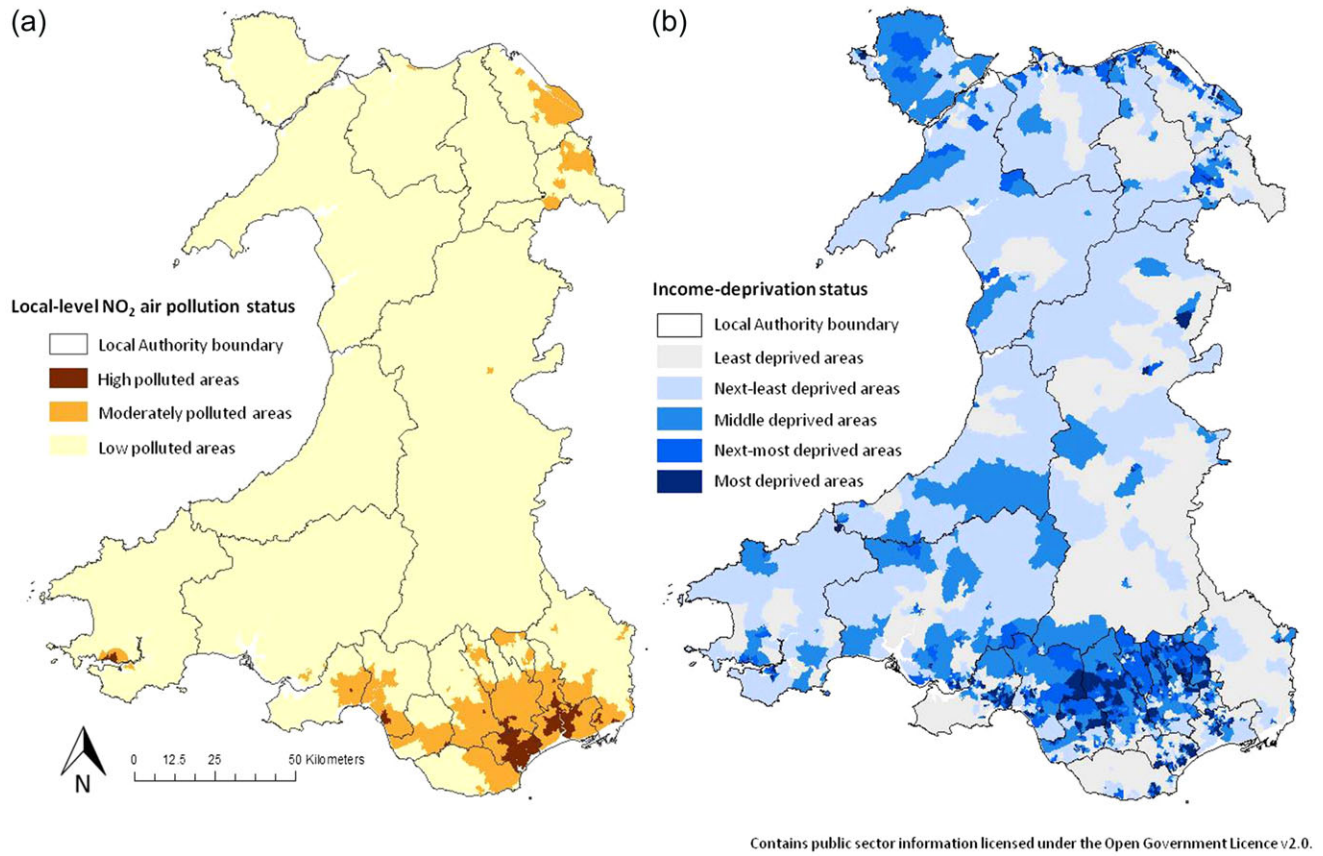

Fig. 1 Map of Wales showing local-level distribution patterns for (**a**) NO_2 air pollution status; and (**b**) income deprivation status.

In the context of deprivation, a marked 'u'-shaped, non-linear NO_2-value distribution pattern was observed across quintiles; average concentrations were highest in 'most' deprived areas and next highest in 'least' deprived areas (Fig. 2). The patterns for PM_{10} and $PM_{2.5}$ were similar to that of NO_2 but less pronounced.

In the context of health, the average annual all-cause non-accidental death count in Wales was 30 035 (Wales EASR = 100.5 per 10 000; 95% CI: 99.4–101.7). Cardiovascular disease accounted for 31% of these (EASR = 30.9 per 10 000; 95% CI: 30.3–31.6), respiratory disease 16% (EASR = 15.7 per 10 000; 95% CI: 15.3–16.2), cerebrovascular disease 8% (EASR = 7.6 per 10 000; 95% CI: 7.3–8.0) and chronic liver disease 1% (EASR = 1.4 per 10 000; 95% CI: 1.3–1.6). For each death, there were 3.3, 9.7, 2.3, and 2.2 times as many hospital admissions for the same diseases, respectively.

Assessing associations

The *air pollution–health* association analysis revealed that rates of only all-cause non-accidental mortality (RR = 1.27; 95% CI: 1.10–1.45) and respiratory disease mortality (RR = 1.43; 95% CI: 1.03–1.96) increased as NO_2 air pollution worsened and were significantly higher in 'high' polluted areas compared with 'low' polluted areas (Table 1). Similar associations were observed for $PM_{2.5}$ (all-cause non-accidental mortality: RR = 1.15; 95% CI: 1.10–1.20; respiratory disease mortality: RR = 1.37; 95% CI: 1.22–1.52) and PM_{10} (all-cause non-accidental mortality: RR = 1.14; 95% CI: 1.08–1.20; respiratory disease mortality: RR = 1.31; 95% CI: 1.15–1.50; respiratory disease morbidity: RR = 1.17; 95% CI: 1.12–1.21).

The *deprivation–health* association analysis showed that income-deprivation status was positively and significantly associated with all health outcomes, especially chronic liver disease mortality and morbidity (Fig. 3). *Deprivation–health* associations were stronger than *air pollution–health* associations. With the exception of the 'control' chronic liver disease outcomes, income-deprivation status was most strongly associated with respiratory disease mortality (RR = 1.97; 95% CI: 1.79–2.17) and morbidity (RR = 2.05; 95% CI: 1.98–2.11).

As for *air pollution–deprivation-health* association assessment, when considered in the context of air pollution, positive

associations between deprivation status and health persisted (Table 2). All health endpoints were positively associated with income-deprivation status; rates were higher in 'most' deprived/'low' polluted areas than in reference 'least' deprived/'low' polluted areas, regardless of air pollution status. Chronic liver disease outcomes continued to be most strongly associated with deprivation status, followed by respiratory disease outcomes. Simultaneously considering income-deprivation and air pollution status (for PM_{10} and $PM_{2.5}$, but not NO_2) strengthened the associations observed previously in the *deprivation-health*-only analysis for only all-cause non-accidental and respiratory disease mortality.

In 'least' deprived areas, rates of all-cause non-accidental and respiratory disease mortality increased as NO_2, PM_{10} and $PM_{2.5}$ air pollution status worsened, but associations were non-significant. In 'most' deprived areas, strong positive associations were observed between all air pollutants and all-cause non-accidental and respiratory disease mortality (Table 1). In these latter areas, for these health outcomes, air pollution increased the significance of *deprivation–health* associations. To illustrate this with an example drawn from the data: for PM_{10}, the respiratory mortality rate was a significant 2.05 times higher in 'low' polluted/'most' deprived areas (RR: 2.05; 95% CI: 1.73–2.41) compared with reference 'low' polluted/'least' deprived areas. Across 'most' deprived areas, as air pollution status worsened associations were strengthened, becoming 2.21 times higher (RR: 2.21; 95% CI: 1.92–2.53) in 'moderately' polluted areas and 2.38 times higher (RR: 2.38; 95% CI: 1.89–2.95) in 'high' polluted areas.

It should be noted that significant negative associations were found in 'most' income-deprived areas between: NO_2 and respiratory disease morbidity; PM_{10} and cardiovascular disease mortality, cerebrovascular and chronic liver disease morbidity; and $PM_{2.5}$ and cardiovascular disease mortality.

Discussion

Main findings

Air pollution concentrations, especially NO_2, showed LSOA-level variation. Average air pollution concentrations were relatively high in both 'most' and 'least' deprived areas, but were highest in the former. Substantial local-level deprivation-related health inequalities were observed; the magnitude of *deprivation–health* associations was greater than *air pollution–health* associations. That said, not accounting for deprivation status, each pollutant was positively and significantly associated with all-cause non-accidental and respiratory disease mortality, and PM_{10} with respiratory disease morbidity too. When considered simultaneously, the interaction between air pollution and deprivation status modified and amplified associations with all-cause non-accidental and respiratory disease mortality endpoints, especially in 'most'

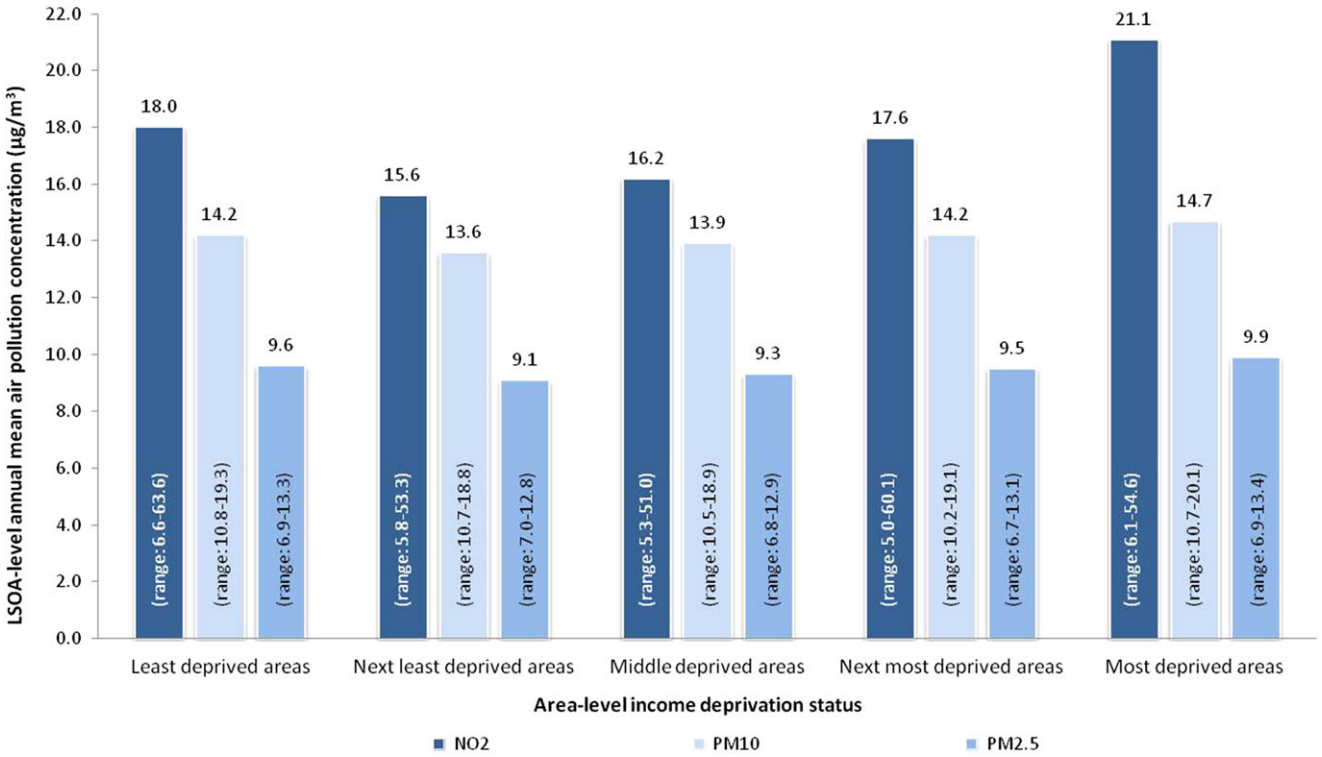

Fig. 2 Local-level annual mean air pollutant concentrations by income-deprivation status.

Table 1 Local-level air pollution status association with health outcomes (holding 'low' polluted areas as reference)

			Low polluted areas (Reference)	*Moderately polluted areas*	*High polluted areas*
Nitrogen dioxide (NO_2)	Mortality rate ratio (95%CI)	All-cause	—	1.02 (0.98 to 1.05)	1.27** (1.10 to 1.45)
		Cardiovascular disease	—	0.93 (0.87 to 0.99)	1.09 (0.82 to 1.41)
		Cerebrovascular disease	—	1.08 (0.96 to 1.23)	1.15 (0.64 to 1.90)
		Respiratory disease	—	1.10* (1.01 to 1.20)	1.43** (1.03 to 1.96)
		Chronic liver disease	—	1.07 (0.67 to 1.37)	1.64 (0.36 to 3.95)
	Morbidity rate ratio (95%CI)	Cardiovascular disease	—	0.93* (0.90 to 0.96)	1.10 (0.95 to 1.26)
		Cerebrovascular disease	—	0.85* (0.78 to 0.93)	1.11 (0.77 to 1.56)
		Respiratory disease	—	0.97 (0.95 to 1.00)	1.13* (1.01 to 1.26)
		Chronic liver disease	—	0.91 (0.74 to 1.11)	1.59 (0.75 to 2.92)
Particulate matter (PM_{10})	Mortality rate ratio (95%CI)	All-cause	—	1.09* (1.06 to 1.11)	1.14** (1.08 to 1.20)
		Cardiovascular disease	—	1.02 (0.98 to 1.07)	1.03 (0.93 to 1.14)
		Cerebrovascular disease	—	1.00 (0.91 to 1.08)	1.11 (0.90 to 1.33)
		Respiratory disease	—	1.21* (1.15 to 1.30)	1.31** (1.15 to 1.50)
		Chronic liver disease	—	1.00 (0.82 to 1.23)	1.36 (0.91 to 2.00)
	Morbidity rate ratio (95%CI)	Cardiovascular disease	—	1.12* (1.09 to 1.14)	1.11* (1.05 to 1.17)
		Cerebrovascular disease	—	1.02 (0.97 to 1.08)	0.95 (0.83 to 1.08)
		Respiratory disease	—	1.16* (1.14 to 1.18)	1.17** (1.12 to 1.21)
		Chronic liver disease	—	1.17 (0.99 to 1.35)	1.03 (0.75 to 1.15)
Particulate matter ($PM_{2.5}$)	Mortality rate ratio (95%CI)	All-cause	—	1.12* (1.09 to 1.14)	1.15** (1.10 to 1.20)
		Cardiovascular disease	—	1.05 (1.00 to 1.09)	1.03 (0.95 to 1.12)
		Cerebrovascular disease	—	1.00 (0.91 to 1.09)	1.12 (0.95 to 1.31)
		Respiratory disease	—	1.28* (1.20 to 1.36)	1.37** (1.22 to 1.52)
		Chronic liver disease	—	1.08 (0.86 to 1.33)	1.39 (0.94 to 1.91)
	Morbidity rate ratio (95%CI)	Cardiovascular disease	—	1.10* (1.05 to 1.15)	1.15* (1.12 to 1.18)
		Cerebrovascular disease	—	1.07 (1.00 to 1.12)	0.93 (0.83 to 1.05)
		Respiratory disease	—	1.22* (1.20 to 1.25)	1.19* (1.14 to 1.23)
		Chronic liver disease	—	1.31 (0.99 to 1.52)	1.31 (1.00 to 1.67)

*Statistically significant result.

**Statistically significant result; RR increased as area-level air pollution status worsened.

deprived areas where Wales' most-vulnerable populations live. While action is needed to reduce air pollution concentrations and associated risks everywhere, for these health outcomes in these areas, lowering air pollution and deprivation status to that of 'low' polluted and 'least' deprived areas could achieve a substantial additional health gain.

What is already known?

The evidence for a socio-economic gradient in health is well-established. The average seven-year life-expectancy difference between 'most' and 'least' deprived areas in Wales[13] and the UK[30] is mostly attributed to multiple deprivation risk factors, especially lifestyle behaviours and choices.[31] This study corroborated findings that *deprivation–health* associations are stronger than *air pollution–health* associations.[18] However, as also found here, air pollution is a known environmental health determinant that adds to already-strong *deprivation–health* associations.[32] This is supported by unequivocal evidence of independent, likely causal relationships between air pollution exposure and cardio-pulmonary and other health impacts.[1]

Several studies have assessed air pollution and deprivation associations. In the US, Canada and New Zealand, higher air pollution levels have been reported in socioeconomically disadvantaged compared with less-deprived communities.[33–38] However, the situation in Europe appears to be less straightforward; findings from studies across Europe have generated mixed results.[39–45] In the UK, Walker *et al.* previously reported findings that are consistent with those of this study, that both 'most' and 'least' deprived areas were disproportionately affected by high NO_2 concentrations.[42] A number of possible explanations for these inconclusive research

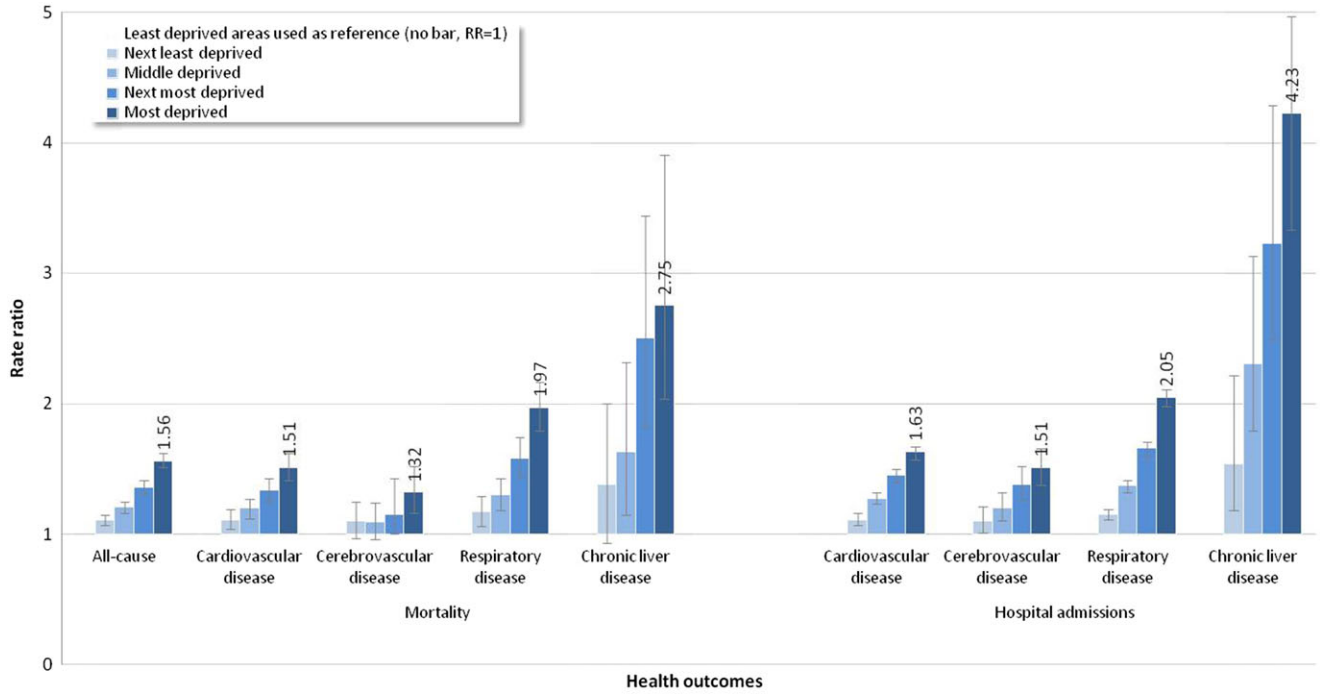

Fig. 3 Local-level income-deprivation status association with health outcomes (holding 'least' deprived areas as reference).

findings have been offered; all relating to characteristics of urbanized areas. For example, a study comparing local, regional and national-level associations between air pollution and socio-economic factors in England and the Netherlands suggested that more-deprived areas are often in close proximity to mixed/high-traffic roads.[23] A study exploring the same relationships (at Local Authority level) in England and Wales explained that areas of mixed deprivation are often adjacently-located in urban areas,[43] which may be the result of city gentrification and land-use planning decisions.[23] Lastly, although beyond the UK context, a study that examined the environmental inequity of traffic-related air pollution in Toronto, Canada, proposed those living in 'least deprived' urban areas tolerate more pollution in lieu of living, social and employment benefits.[46]

A number of studies have also explored air pollution and deprivation associations in the context of vulnerable people affected. Environmental justice analyses of air quality in the UK have found that children are disproportionately exposed (and are more vulnerable) to higher levels of air pollution.[44,47] This present study found that 'most deprived' areas contained the highest proportion of children aged <15 years in any deprivation quintile (24%; estimated population: 122 458). Additionally, Laxen *et al.*,[48] unlike Fecht *et al.*,[23] found that older people were disproportionately exposed to air pollution in the city of Bristol, UK. This study identified that 'least' deprived areas had high air pollution concentrations and contained the highest proportion of older people aged 75+ years in any deprivation quintile (23%; estimated population: 57 332). Despite having a high proportion of older people, it should be noted that less-deprived populations are generally healthier and so are likely to be less susceptible to the effects of air pollution.[49]

A relatively small number of studies have extended the research boundaries beyond air pollution and deprivation to also consider health impacts. These have generally found that area-level air pollution status is associated with significant increases in all-cause non-accidental, cardiovascular and respiratory disease mortality risk in high-deprivation compared with less-deprived areas.[18,25,50–56] Weak relationships of air pollution and deprivation with morbidity (respiratory hospital admissions) have been reported.[51,57] While it is often difficult to compare studies because of inconsistencies in research approaches and methods, in the main, interactions between air pollution and socio-economic factors have been found to modify and compound the health effects associated with each variable individually.[53,58,59]

To summarize, a balanced review of European evidence suggests the general pattern is: that deprived people, while not always exposed to higher levels of air pollution, are more likely to suffer greater harm as a consequence of their exposure since they are more vulnerable to its effects.[45]

Table 2 Air pollution-deprivation-health associations (holding 'low' polluted and 'least' deprived areas as reference)

				Air pollution status		
			Deprivation status	*Low*	*Moderate*	*High*
Nitrogen dioxide (NO_2)	Mortality rate ratio (95%CI)	All-cause	Least	—	1.01 (0.92 to 1.07)	1.09 (0.28 to 2.09)
			Most	1.41* (1.36 to 1.45)	1.43* (1.34 to 1.52)	1.62** (1.37 to 1.89)
		Cardiovascular	Least	—	0.94 (0.84 to 1.06)	1.17 (0.03 to 3.95)
		disease	Most	1.40* (1.32 to 1.48)	1.26* (1.14 to 1.40)	1.32 (0.93 to 1.78)
		Cerebrovascular	Least	—	1.04 (0.83 to 1.27)	0.41 (0.01 to 2.84)
		disease	Most	1.15* (1.03 to 1.29)	1.31* (1.05 to 1.59)	1.39 (0.67 to 2.44)
		Respiratory	Least	—	1.14 (0.97 to 1.32)	1.17 (0.04 to 15.94)
		disease	Most	1.70* (1.57 to 1.84)	1.80* (1.58 to 2.06)	2.10** (1.38 to 3.03)
		Chronic liver	Least	—	1.00 (0.54 to 1.88)	0.67 (0.22 to 4.58)
		disease	Most	2.33* (1.81 to 3.17)	2.33* (1.49 to 3.62)	3.56 (0.88 to 8.94)
	Mortality rate ratio (95%CI)	Cardiovascular	Least	—	0.92* (0.86 to 0.98)	1.05 (0.24 to 2.22)
		disease	Most	1.51* (1.47 to 1.56)	1.39* (1.31 to 1.47)	1.44* (1.20 to 1.69)
		Cerebrovascular	Least	—	0.80* (0.68 to 0.94)	0.95 (0.01 to 6.81)
		disease	Most	1.42* (1.32 to 1.53)	1.22* (1.05 to 1.39)	1.37 (0.87 to 2.05)
		Respiratory	Least	—	0.92* (0.87 to 0.97)	1.02 (0.11 to 1.65)
		disease	Most	1.80* (1.75 to 1.85)	1.73* (1.66 to 1.80)	1.70* (1.49 to 1.93)
		Chronic liver	Least	—	0.75 (0.42 to 1.25)	0.81 (0.13 to 6.44)
		disease	Most	3.25* (2.66 to 4.11)	2.69* (1.96 to 3.71)	4.13* (1.79 to 8.24)
Particulate matter (PM_{10})	Mortality rate ratio (95%CI)	All-cause	Least	—	1.02 (0.96 to 1.08)	1.06 (0.91 to 1.24)
			Most	1.56* (1.46 to 1.66)	1.58* (1.50 to 1.66)	1.65** (1.50 to 1.80)
		Cardiovascular	Least	—	0.95 (0.86 to 1.05)	1.05 (0.78 to 1.38)
		disease	Most	1.54* (1.37 to 1.73)	1.46* (1.33 to 1.61)	1.38* (1.16 to 1.64)
		Cerebrovascular	Least	—	1.02 (0.82 to 1.24)	1.21 (0.68 to 1.96)
		disease	Most	1.33* (1.04 to 1.68)	1.36* (1.11 to 1.64)	1.33 (0.91 to 1.87)
		Respiratory	Least	—	1.19* (1.02 to 1.39)	1.35 (0.86 to 1.95)
		disease	Most	2.05* (1.73 to 2.41)	2.21* (1.92 to 2.53)	2.38** (1.89 to 2.95)
		Chronic liver	Least	—	1.14 (0.60 to 2.17)	1.57 (0.28 to 5.50)
		disease	Most	3.71* (2.07 to 7.16)	2.71* (1.62 to 5.04)	4.71* (2.32 to 9.79)
	Mortality rate ratio (95%CI)	Cardiovascular	Least	—	1.04 (0.98 to 1.10)	1.03 (0.8 to 1.20)
		disease	Most	1.65* (1.55 to 1.76)	1.68* (1.60 to 1.77)	1.57* (1.43 to 1.72)
		Cerebrovascular	Least	—	0.97 (0.85 to 1.11)	0.93 (0.61 to 1.35)
		disease	Most	1.58* (1.35 to 1.84)	1.48* (1.30 to 1.68)	1.31* (1.03 to 1.66)
		Respiratory	Least	—	1.04 (0.98 to 1.09)	0.96 (0.84 to 1.09)
		disease	Most	2.03* (1.92 to 2.15)	2.11* (2.01 to 2.21)	2.02* (1.88 to 2.18)
		Chronic liver	Least	—	1.08 (0.70 to 1.82)	0.83 (0.16 to 2.82)
		disease	Most	5.17* (3.39 to 8.16)	4.58* (3.12 to 7.01)	3.92 (0.22 to 6.84)
Particulate matter ($PM_{2.5}$)	Mortality rate ratio (95%CI)	All-cause	Least	—	1.04 (0.98 to 1.10)	1.08 (0.91 to 1.18)
			Most	1.57* (1.49 to 1.70)	1.58* (1.50 to 1.67)	1.61** (1.48 to 1.74)
		Cardiovascular	Least	—	0.96 (0.87 to 1.07)	0.97 (0.79 to 1.18)
		disease	Most	1.57* (1.38 to 1.78)	1.48* (1.34 to 1.63)	1.40* (1.20 to 1.62)
		Cerebrovascular	Least	—	1.05 (0.86 to 1.29)	1.11 (0.74 to 1.59)
		disease	Most	1.41* (1.07 to 1.84)	1.33* (1.09 to 1.63)	1.50* (1.09 to 2.01)
		Respiratory	Least	—	1.21* (1.04 to 1.42)	1.26 (0.89 to 1.60)
		disease	Most	2.15* (1.79 to 2.59)	2.19* (1.90 to 2.53)	2.34** (1.91 to 2.85)
		Chronic liver	Least	—	1.14 (0.60 to 2.08)	1.43 (0.40 to 4.09)
		disease	Most	4.29* (2.33 to 8.30)	2.86* (1.67 to 5.20)	3.71* (1.92 to 7.50)
			Least	—	1.05 (0.99 to 1.11)	0.95 (0.77 to 1.06)

Continued

Table 2 Continued

				Air pollution status		
			Deprivation status	*Low*	*Moderate*	*High*
	Mortality rate ratio (95%CI)	Cardiovascular disease	Most	1.60* (1.48 to 1.72)	1.71* (1.62 to 1.80)	1.56* (1.44 to 1.69)
		Cerebrovascular	Least	—	0.99 (0.86 to 1.13)	0.79 (0.59 to 1.06)
		disease	Most	1.54* (1.29 to 1.83)	1.50* (1.32 to 1.71)	1.76* (1.46 to 2.12)
		Respiratory	Least	—	1.06* (1.01 to 1.12)	0.94 (0.85 to 1.04)
		disease	Most	2.03* (1.91 to 2.15)	2.14 * (2.04 to 2.24)	2.04* (1.91 to 2.18)
		Chronic liver	Least	—	1.17 (0.72 to 1.88)	0.83 (0.63 to 1.88)
		disease	Most	4.75* (2.99 to 7.67)	4.58* (3.15 to 7.05)	4.58* (2.86 to 7.56)

*Statistically significant result.

**Statistically significant result; RR increased as area-level air pollution status worsened.

What this study adds

Prior to this study, little was known about the relationships between air pollution, deprivation and health in Wales, especially at the local level. Findings raise important issues that should now inform debates around the future development of LAQM and public health policy and practice in Wales and beyond. The significant, and complex, interactions between these variables justify air pollution problems and solutions not being considered in isolation. Rather, air pollution problems should be regarded as a local public health priority that is inextricably linked with other behavioural, societal and environmental determinants of health. For example, people living in poorly-designed communities where sustainability and active travel is not promoted may be overly-dependent on the use of cars; this may lead to physical inactivity that, when coupled with other more-likely behaviours in most deprived areas such as high alcohol consumption, poor diet and smoking, increases the risk of poor health outcomes like cardio-respiratory diseases, obesity, diabetes, cancer and mental ill-health. This poor health status makes people susceptible to the effects of air pollution (which is highest in most deprived areas) and exacerbates problems.

It remains important to reduce air pollution exposures and associated risks for all. However, this study shows that greater public health gains (maximized risk reduction and minimized inequalities) can result not from simply reducing air pollution and exposure potential, but by doing so alongside efforts to tackle broader health determinants in areas where health needs are greatest. Typically, this is in 'most' deprived and polluted areas where, as this study found, rates of cardio-respiratory mortality could be up to 2.4 times lower if air pollution and income-deprivation status were reduced to those of 'low' polluted and 'least' deprived areas.

Considering local problems and solutions in the broadest possible public health context must be the priority. Air pollution mitigation and public health intervention should be evidence-informed, targeted and co-ordinated. Public health agencies and professionals have a valuable contribution to make to this work. Specifically, in the context of LAQM policy and practice, greater public health integration and engagement in LAQM can add value through:

- Risk assessment – data sharing, linkage, analysis and interpretation can improve population risk assessments. Results will be more comprehensive, accurate and meaningful in terms of scoping problems, defining at-risk populations, and understanding relationships, causes and solutions. Appreciating this 'big picture' can, in turn, inform targeted risk communications and interventions.
- Management – collaborating to achieve air quality and public health co-benefits through active travel interventions (encouraging walking and cycling over vehicle use). Also, implementing strategies to improve individual and community baseline-health status and thus reduce susceptibility (e.g. promoting nutrition, smoking cessation, service access), educating people to change behaviours and advocating for the design of sustainable and healthy communities, and the separation of people and pollution sources, by working with local Planning Authorities to inform decision-making.[60]
- Intervention and policy development – facilitating intervention evaluations (that consider air pollution reduction *and* health impacts together) to determine what works in

real-world situations. Also, advocating for, and providing authority, leadership and autonomy to bring about evidence-based change through stronger policy connection and change.

Limitations

A limitation of ecological studies generally is assuming that hazards, risks and outcomes are spread evenly across defined areas and populations. Since this study assessed air pollution, deprivation and health associations by using aggregated area-level data, the risk of the 'ecological fallacy'[61] – making inferences about individuals from area/population-level analyses – was minimized. Assumptions around homogeneity, and separate air pollutant analyses that did not account for pollutant synergies,[62] may have actually underestimated the strength of the local-level associations found. It is also important to note that, as a cross-sectional study, causal inference cannot be drawn from the findings.

This study's emphasis on exploring 'local' associations meant that, as with all small-area analyses, there were limitations of using high-resolution data. Limitations include: numbers of health events over short periods may be small and give rise to health burden estimates affected by chance and random variation, measures of exposure are approximate, boundaries and populations may change over short time-frames, and allocating events to areas is difficult. In some instances the relatively small numbers of health events gave rise to some results that were not expected such as the significant negative associations between area-level PM status and cardiovascular disease mortality. However, in the main, selecting LSOAs as the geographical study unit, and linking all data at this level, made this study more robust. Data were aggregated based on matched area-level characteristics (air pollution and income-deprivation status) to avoid problems associated with small numbers, data for three years were used to smooth annual variations, and LSOA boundaries were consistent over the study period. Also, despite varying in size geographically, the limited population variation of LSOAs facilitated comparisons across small areas, compared with geographic units used in ecological analyses historically such as electoral 'wards'.

Modelled air pollution data were preferred over measured data from discrete monitoring points (where distances, and probability of pollution variation, between receptor and the nearest monitor can be significant) as they more accurately reflect area concentrations and population exposures.[15,55] The modelled data used in this study are validated annually against measured data from air pollution monitoring stations. While this increases confidence in area-level modelled air pollution data, it should be noted that such area-level estimates may not correspond exactly with actual personal exposure which is influenced by an individual's mobility, time spent indoors and outdoors, and activity patterns, levels and types. Given that this ecological study was concerned with area-level relationships only, it was inappropriate to attempt to estimate the exposure of individuals; this avoided bias from exposure misclassification.

Only one measure of deprivation – income deprivation – was used as an indicator for area-level multiple deprivation status. Doing so avoided 'double counting' the health and air pollution components that would have occurred had the summary WIMD score been used and therefore minimized the possibility of delivering skewed results.[7,18,23]

It was not possible to account for all confounding factors. Smoking, for example, is a key risk factor for the health outcomes of interest in this study, but only Local Authority-level smoking prevalence data were available which were based on self-reported survey responses from a sample of the Welsh population. Using data such as these (not specific to small areas), would have yielded little bias-reduction since large-area summary data are often grossly inadequate to ensure effective control.[63] Attempting to disaggregate these data would have introduced greater uncertainty and bias. Other studies that have explored air pollution, deprivation and health associations have confirmed that adjusting for smoking behaviour where available at larger geographies does not significantly attenuate results.[50,51,57] The use of chronic liver disease 'control' outcomes did however inform the interpretation of results.

Given that some important data were not available by LSOA, a simple approach to investigating local-level relationships was selected over complex regression techniques. This approach is intended to be understandable and meaningful to policy-makers and the public. However, it may be perceived by some to be overly-simplistic. In response, it is argued that, although a small-area study, the denominator population is over 3 million people – a sample size that reduces the effect of confounders. Additionally, population variations are accounted for to a large extent through age-standardization.

Conclusion

Air pollution concentrations were highest in 'most' deprived areas. Separately, *deprivation–health* associations were stronger than *air pollution–health* associations. Considered simultaneously, air pollution added to *deprivation–health* associations for some health outcomes. Interactions between air pollution and deprivation modified and amplified associations with

all-cause non-accidental and respiratory disease mortality, especially in 'most' deprived areas where Wales' most-vulnerable populations live.

Air pollution, deprivation and health are inextricably linked. There is merit in implementing measures to reduce air pollution concentrations and exposures for all, just as there is in tackling deprivation-related risk factors. However, if local air pollution problems and solutions are considered in the context of wider health determinants, and air pollution mitigation and public health interventions are aligned and targeted in areas where health needs are highest, greater health gains (reduced health risks and inequalities) can be achieved. To facilitate this, achieving greater public health integration and engagement in LAQM policy and practice must be prioritized in Wales and beyond.

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