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Long-term Exposure to Ambient PM_{2.5} and Population Health: Evidence from Longitudinally-linked Census Data

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Abstract

Extensive evidence shows exposure to ambient PM_{2.5} is associated with a wide range of poor health outcomes. But few studies examine genuinely long-run pollution exposures in nationally representative data. This study does so, exploiting longitudinally-linked Census data for Northern Ireland, linked to annual average PM_{2.5} concentrations at the 1km grid-square level from 2002-2010, exploiting complete residential histories. We show strong unconditional associations between PM_{2.5} exposure, self-rated general health, disability, and all available (eleven) domain-specific health measures in the data. Associations with poor general health, chronic illness, breathing difficulties, mobility difficulties, and deafness are robust to extensive conditioning and to further analysis designed to examine sensitivity to unobserved confounders.

Introduction

The World Health Organization (WHO) attributes 4.2 million deaths worldwide per year to exposure to ambient (outside) air pollution.¹ In addition to mortality (e.g., Orrelano et al., 2020), there is extensive evidence in the epidemiological literature that exposure (both short- and long-term) to ambient air pollution, and specifically to PM_{2.5}, is associated with a wide range of poor health outcomes (WHO, 2013). These morbidity outcomes include, but are not limited to, cardiovascular diseases (Brook et al., 2010; Pope and Dockery, 2006); cerebrovascular disease (Chan et al., 2006); respiratory diseases (Xing et al., 2016); age-related cognitive decline and dementia (Paul et al., 2019; Peters et al., 2019; Power et al., 2016; Delgado-Saborit et al., 2020); diabetes (Bowe et al., 2018; Yang et al., 2020); sight loss (Chua et al., 2019); and also with how people perceive their general health (Klompmaker et al., 2019; Sun and Gu, 2008). For some of these outcomes there are counterexamples in the literature, e.g., a recent meta-analysis finds evidence of an association with diabetes for North America but not for Europe (see Yang et al., 2020). For some other morbidity outcomes existing evidence is either sparse or more mixed, e.g., mental health (Ventriglio et al., 2021); hearing loss (Yuan et al., 2022); and rheumatoid arthritis (Di et al., 2020).

A key problem facing this literature is that people in higher pollution areas may have worse health outcomes for reasons other than exposure to ambient air pollution, and the available observational data often fall short of research aspirations to estimate *causal* pollution effects. Randomised controlled trials are infeasible and studies have generally not been able to exploit natural experiments or convincing instrumental variables approaches that can explicitly identify *long-term* pollution effects (although there are isolated exceptions, e.g., Bishop et al., 2018). Studies therefore typically rely on multivariate regression or matching approaches, controlling for observed potentially confounding factors as far as the data allow. Often, however, the set of individual characteristics and contextual factors included in the data is limited, leaving others as unobserved potential confounders (Sheppard et al., 2012; Weuve et al., 2015). The impact of long-term exposure to pollution is also typically extrapolated from short-term exposure to pollution (Power et al., 2016; COMEAP, 2018), because measuring long-term exposure, especially at a local level, requires longitudinal data that track sufficiently large samples of individuals and their addresses, with diverse exposures, over long periods. Further, studies of long-term pollution exposure effects are rarely able to examine a wide range

¹ <https://www.who.int/teams/environment-climate-change-and-health/air-quality-and-health/health-impacts/exposure-air-pollution>.

of health outcomes and conditions. For example, a recent study using UK Biobank data to examine multimorbidity (exploiting excellent data on multiple outcomes) was limited to single-year estimates of exposure (Ronaldson et al., 2022).

In this study we use rich unit-record longitudinal data, tracking a large and representative sample of the population from 2001-2011 in Northern Ireland, to examine, for the first time, the conditional associations between *long-term* exposure to ambient PM_{2.5}, self-rated (general) health, disability, and eleven domain-specific health outcomes measured by the 2011 Census. These domain-specific outcomes include experiencing long-running difficulties with breathing, chronic illness, and experiencing frequent periods of confusion or memory loss. Because the data were drawn from linked Censuses with address records in intervening years, they enable estimation with a high degree of control for potentially confounding factors at the individual level, the household level and the neighbourhood level. We also estimate whether conditional associations vary between different demographic and socio-economic groups. Robustness to the presence of unobserved confounders is assessed in two extensions, first following the approach of Oster (2019), and second by including an extensive set of fine-grained and year-specific neighbourhood fixed effects throughout the exposure period.

Methods

Data

We link data from the Northern Ireland Longitudinal Study (NILS) with 1x1km grid square annual mean pollution data published by the UK Government Department for Environment, Food and Rural Affairs. The NILS is a large-scale data linkage project containing a 28% representative sample of the Northern Ireland (NI) population. This sample was initially drawn in 2001 from the NI Health Card Registration System and is updated biannually to reflect changes in births, deaths and immigration/migration. Importantly, the NILS contains biannual residential address information and a rich set of personal- and household-level information from Census returns for 2001 and 2011 (O'Reilly et al., 2012). The pollution data, matched at the residential property level to NILS participants, provide annual 1x1km grid square modelled pollution levels from 2002-2011 for PM_{2.5}. These data are produced on an ongoing basis for the UK Government's air quality assessments (Brookes et al., 2020).

Analytical Sample

Our analysis sample contains all NILES members present in both the 2001 and 2011 Censuses, who were aged 26-84 at the time of the 2011 Census, with full address records over this ten-year period (and therefore no missing pollution exposure data), and without missing data on outcomes and included covariates. This gives a total of 220,166 individuals, each tracked for ten years. In the Supplementary Material we show that our conclusions are robust to inclusion of those with partial records. The analysis sample closely matches the full NILES (adult) sample in terms of health outcomes measured and individual, household and contextual characteristics available from the 2011 Census, although those whose country of birth was outside Northern Ireland are under-represented given the requirement to be enumerated in both 2001 and 2011 Censuses. Our outcome variables, drawn from the 2011 Census, are measured at the end of this period, so for estimation purposes these data are treated as a cross section to examine the associations between 2011 reported health outcomes and exposure to pollution over the 2002-2010 period, albeit with individual and household-level covariates measured prior to exposure (in 2001). In an extension we also include neighbourhood-year fixed effects throughout the exposure period.

Outcome variables

There are several outcome variables, all of which are self-reported (or reported by the member of the household filling in the Census form) in the 2011 Census, but with varying levels of specificity. Our primary outcome variable is self-rated health. The 2011 Census contains a general health question as follows: *How is your health in general?* Responses are on a 5-point Likert scale ranging from very good to very bad. For consistency with the other health outcomes (all of which are binary) we collapse the 5-point scale into a binary outcome where 1 indicates bad/very bad self-rated health (which we label *poor general health*), and 0 indicates fair, good or very good self-rated health. This question was also asked in the 2001 Census, enabling a degree of control for prior health.

Second, we examine associations between pollution exposure and activity-limiting disability exploiting the following question in the 2011 Census: *Are your day-to-day activities limited because of a health problem or disability which has lasted, or is expected to last, at least 12 months? Include problems related to old age.* Possible responses are: *Yes, limited a lot; Yes, limited a little; No.* In line with the definition of disability used in the 1995 Disability Discrimination Act, we treat those ticking the first box (*Yes, limited a lot*) as having an activity-

limiting disability, merging the two other categories into a single *no/not substantially* limited category. A yes/no version of this question was also asked in the 2001 Census.

We then generate a further eleven domain-specific health outcome variables. The 2011 Census (but not the 2001 Census) also contains the following question on specific health domains and conditions: *Do you have any of the following conditions which have lasted, or are expected to last, at least 12 months?* There are multiple options (and respondents could tick more than one) as follows: *Deafness or partial hearing loss; Blindness or partial sight loss; Communication difficulty (a difficulty with speaking or making yourself understood); A mobility or dexterity difficulty (a condition that substantially limits one or more basic physical activities such as walking, climbing stairs, lifting or carrying); A learning difficulty, an intellectual difficulty, or a social or behavioural difficulty; An emotional, psychological or mental health condition (such as depression or schizophrenia); Long-term pain or discomfort; Shortness of breath or difficulty breathing (such as asthma); Frequent periods of confusion or memory loss; A chronic illness (such as cancer, HIV, diabetes, heart disease or epilepsy); Other condition.* We construct binary indicators for each domain, equal to 1 for those who tick the relevant box and 0 otherwise. This extensive list of health outcomes was unique to the Northern Ireland 2011 Census. The equivalents for Scotland and England and Wales collected health data only on subjective general health and disability, and for Scotland (but not England and Wales) on a less extensive set of health domains excluding breathing difficulties and memory loss, two key health outcomes in this context.

Although extensive evidence exists internationally for associations between many of these (or closely related) outcomes and exposure to ambient PM_{2.5} air pollution (e.g., consider the studies cited earlier on cardiovascular disease, respiratory ill health, dementia, self-rated general health, other chronic illnesses), for others the evidence is relatively sparse, e.g., adult exposure effects on learning difficulties (Xu et al., 2016). There is also growing evidence of biological causal mechanisms for exposure to PM_{2.5} to impact on at least some of these outcomes, especially for cardiovascular disease (Brook et al., 2010; Rajagopalan et al., 2018). For some other outcomes, effects may occur indirectly via the cardiovascular system, e.g., for cognitive decline and neurodegenerative diseases, although other causal mechanisms have also been suggested, e.g., accession in external brain magnetite (Baumgart et al., 2015; Gorelick et al., 2011; Qiu and Fratiglioni, 2015; Maher et al., 2016). There are also outcomes, however, where biological mechanisms may be more tentative or exposure in utero or during childhood may be more salient than exposure during adulthood, e.g., learning difficulties. A detailed

integrated assessment of this literature, including an assessment of biological plausibility across a wide range of health outcomes, is provided by EPA (2019).

Table 1 presents sample proportions for each of these outcome variables. Proportions reporting health problems range from 16.5% (mobility or dexterity difficulties) to 1.2% (learning difficulties), with 8.1% reporting poor general health. Measurement error in our outcome variables is possible, given their self/proxy-reported nature (for a recent discussion see Davillas et al., 2023). If random in nature (or at least conditionally random once observed characteristics are adjusted for), however, it will not impart bias, although it may reduce the precision of our estimates.

Table 1: Means of Outcome Variables

Health Outcome	Sample Proportion
Poor General Health	0.081
Long-Term Limiting Illness	0.162
Other Health Condition	0.069
Blindness or Partial Sight Loss	0.019
Communication Difficulty	0.013
Mobility or Dexterity Difficulty	0.165
Learning, Intellectual or Social/Behavioral Difficulty	0.012
Emotional, Psychological or Mental Health Condition	0.080
Long-term Pain or Discomfort	0.157
Shortness of Breath or Difficulty Breathing	0.104
Frequent Confusion or Memory Loss	0.022
Chronic Illness	0.099
Deafness or Partial Hearing Loss	0.072
Observations	220166

Notes: Table reports the (unweighted) proportion of individuals in the analysis sample reporting each health outcome in 2011.

Exposure variable

The pollution data are drawn from those used by the UK government on an ongoing basis to compile the UK air quality pollutant emissions inventory (Dibben and Clemens, 2015; Clemens et al., 2017). Concentrations are calculated by aggregating contribution values from a variety of sources (e.g., large and small point sources as well as area and distance sources) using various inputs, including the UK National Atmospheric Emissions Inventory (Brookes et al., 2020). The models used to obtain these concentrations were calibrated using data from the UK national monitoring network and overall performance was assessed using data from monitoring

sites not used in the calibration exercise. Modelled pollution data of this kind have been widely used in the international literature on the health effects of ambient air pollution (e.g., McGuinn et al., 2019; Fuks et al., 2014; Chen et al., 2017; Hystad et al., 2011), including for Northern Ireland (Jahanshahi et al., 2022), and remain the most widely accepted way to obtain pollution exposures with full population coverage. Unlike potential measurement error in the outcome variables, even random measurement error in the exposure variable may bias estimated pollution impacts. The most likely direction of any such bias is towards zero (attenuation bias). We return to this point later in the discussion.

The pollution-NILS match results in each sample member receiving two annual average pollution values for PM_{2.5} – given as concentrations in micrograms per cubic meter – in each year, the first based on their April address and the second based on their October address. To account for within-year changes in exposure due to address changes, we calculate the mean of these two values for individuals who change address between April and October. For stayers, the annual average is the same in both months. This generates a series of annual mean PM_{2.5} concentrations for each person between 2002 and 2010. In our analysis, we estimate each person’s long-term pollution exposure by calculating their mean concentration over the whole period. We conduct a similar exercise for NO₂ and SO₂ but analyse pollutants separately given their intercorrelation coupled with the potential for noise in their measurement (for a discussion see COMEAP, 2018). As in most studies in this literature, the estimated PM_{2.5} effects presented here may therefore, to some extent, include the impacts of these and other correlated pollutants.

Descriptive statistics for PM_{2.5} pollution exposure in our sample are presented in Table 2. We report a population-weighted average exposure over the relevant nine-year period – this is the first study to do so for NI – of 8.2µg/m³. As this is a long-term average concentration, it is not strictly comparable to an annual average. Having said that, were this interpreted as an annual mean, the average exposure level to PM_{2.5} would clearly exceed the 2021 WHO Air Quality Guideline (AQG), which specifies an annual mean threshold of 5µg/m³, although it falls below the relevant 2005 AQG.² There are no sample members whose long-term average PM_{2.5} exposure over this period falls below the 2021 AQG level.

² <https://apps.who.int/iris/bitstream/handle/10665/345329/9789240034228-eng.pdf?sequence=1&isAllowed=y>

Table 2: PM_{2.5} Pollution in Northern Ireland, 2002-2010

	Population weighted Mean	Standard Deviation	Minimum	Maximum
Annual average exposure, $\mu\text{g}/\text{m}^3$	8.2	1.5	5.4	13.3

Notes: The Table reports summary statistics for PM_{2.5} in $\mu\text{g}/\text{m}^3$. The 2021 World Health Organization annual average guideline level for PM_{2.5} is 5 $\mu\text{g}/\text{m}^3$.

Covariates

A key difficulty facing the air pollution and health literature is that people in higher pollution areas may have worse health outcomes for reasons other than exposure to ambient air pollution (Chen et al., 2021; Deryugina et al., 2019). Natural experiments are one way to overcome this difficulty, but the literature has struggled to find suitable examples in the context of *long-term* pollution effects. In a multivariate regression framework often the best that can be done is to control for potential confounders as far as possible, so that conditional associations are at least interpretable as getting closer to capturing causal effects, albeit under strong assumptions. Previous studies have identified potential confounders at the individual, household, and neighbourhood level (e.g. Power et al., 2016; Bowe et al., 2018). In our study, the 2001 Census link allows construction of a rich set of individual, neighbourhood and household-level socio-economic and demographic control variables which, if omitted, could confound our estimates of the relationships between our outcome variables and pollution exposures. These covariates cover many of the same dimensions and offer a similar degree of control to those used in Chen et al. (2021). All these variables are listed, along with their unweighted sample means, in Table 3. We supplement these covariates with local neighbourhood dummies for area of residence in 2011 in order to control for remaining unmeasured factors at the local area level at the time outcomes were measured.

Table 3: Sample Means of Covariates

	Control Variable	Sample Mean / Proportion
<i>Individual Characteristics</i>	Female	0.536
	Male	0.464
	Aged 16-19 in 2001	0.068
	20-29	0.169
	30-39	0.233
	40-49	0.211
	50-59	0.175
	60-69	0.111
	70-75	0.033
	Born in Northern Ireland	0.924
	Rest of the UK	0.042
	Republic of Ireland (ROI)	0.020
	Born Elsewhere	0.014
	No Educational Qualifications	0.410
	Below Degree or Equivalent	0.429
	Degree, Equivalent or above	0.161
	Employed	0.515
	Self-employed	0.084
	Unemployed	0.037
	Retired	0.098
	Student	0.057
	Looking after Home/Family	0.083
	Long-Term Sick	0.086
	Other Inactive	0.040
	Never Married	0.298
	Married	0.584
	Separated/Divorced/Widowed	0.118
	Catholic	0.382
	Protestant or Other Christian/Religion	0.498
	No Religion or None Stated	0.121
	Good General Health	0.676
	Fairly Good General Health	0.215
	Not Good General Health	0.109
No Long-Term AL Illness	0.804	
Has a Long-Term AL Illness	0.196	
<i>Household Characteristics</i>	Married Couple Household	0.720
	Cohabiting Couple	0.046
	Lone Parent	0.121
	Single Person	0.091
	Other Type of Household	0.021
	0 Dependent Children in Household	0.520
	1	0.184
	2	0.175
	3+ Dependent Children	0.121
	0 Cars in Household	0.143
	1	0.425
	2	0.326
	3+ Cars	0.105
	House is Owner-Occupied	0.798
	Social Rented	0.152
	Private Rented	0.050
	Observations	220166

Notes: Table reports proportions for individual and household control variables. All variables are measured in 2001.

Approach to Estimation

We conduct multivariate analysis in the form of cross-section linear regressions (linear probability models) for poor general health, disability, and each of the eleven domain-specific binary health outcomes and conditions. In the Supplementary Material we show that our conclusions are robust to estimation using logit models in place of linear probability models, along with a range of other sensitivity analysis.

Initially, each outcome variable is regressed on individual-level long-term exposure to $PM_{2.5}$, providing estimates of the unconditional associations between Census health outcomes and long-term exposure to ambient air pollution for the analysis sample (Model 1). Next, the full set of individual and household control variables as of 2001 is included (Model 2). Third, we supplement this model with 2011 neighbourhood fixed effects (at the electoral ward level) to adjust for common neighbourhood-level factors correlated with both exposure and outcomes (Model 3). We treat this neighbourhood fixed effects model as our workhorse model. To explore whether pollution effects vary across different socio-demographic groups, we also estimate versions of this model where we interact pollution exposure with age, gender, prior health, and household tenure in 2001.

Even when extensively conditioned on observable individual and household characteristics together with 2011 neighbourhood fixed effects, however, estimated associations may still be driven in whole or in part by omitted differences between sample members that are correlated with both exposure to ambient $PM_{2.5}$ pollution and self-reported health. If the sign of any resulting omitted variables bias is positive, as seems most likely because we expect pollution to be positively associated with other risk factors for ill-health, positive associations between exposure and poor health outcomes may not be informative about potential pollution effects.

We seek to address this issue in two alternative ways. First, we follow the approach suggested by Oster (2019) in assuming that changes in estimated coefficients and R-squared after inclusion of observed controls (i.e., after accounting for selection on observed confounders) can be informative about the potential role of selection on unobserved confounders in our estimated pollution effects. Several existing studies adopt a similar approach in the context of air pollution and health (e.g., Yuda, 2020; Wang et al., 2019; Guo and Fu, 2019; Ebenstein et al., 2017). Specifically, we apply this Oster-style analysis to the neighbourhood fixed effects estimates from Model 3, following the approach of Bryan et al. (2022). Among the results presented from this Oster analysis are bias-corrected regression coefficients assuming proportional selection from observed and unobserved confounders.

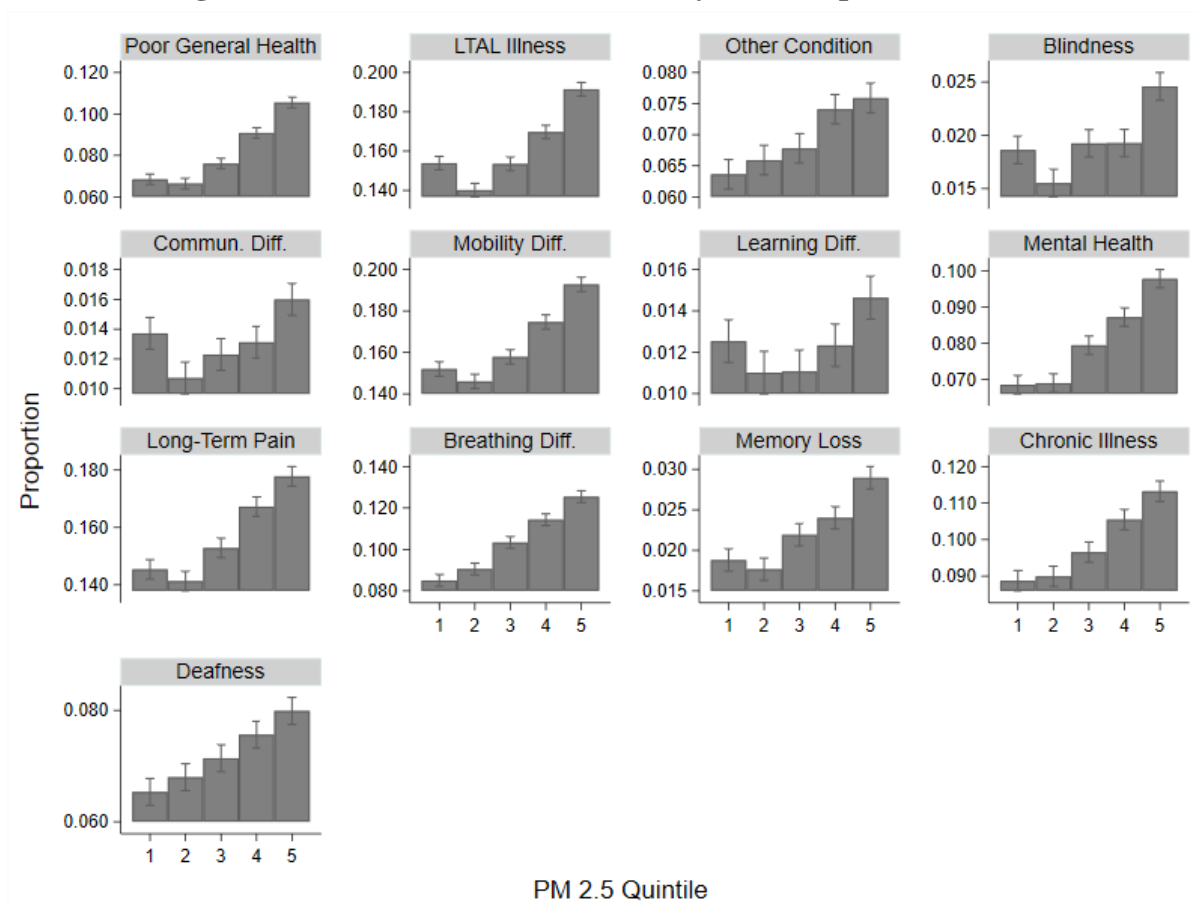
Finding that bias-corrected coefficients remain positive, non-trivial in magnitude and statistically significant at standard levels provides suggestive evidence that associations are qualitatively robust to selection on unobservables. Oster (2019) suggests that where selection bias acts to exaggerate estimated effects, such estimates might reasonably be interpreted as lower bounds on potential causal effects. This interpretation can also hold in the presence of attenuation bias due to measurement error in the exposure variable.

Second, we construct an extended model which adjusts for unobservables more directly by including a full set of neighborhood*year fixed effects for the whole period from 2001-2011, exploiting the complete residential histories that are a feature of these data (Model 4). These Model 4 estimates identify pollution exposure effects net of neighbourhood-level confounders throughout the entire exposure period. The trade-off, however, is substantially larger confidence intervals given that we lose some of the between-individual variation in pollution exposures by taking this step.

Results

Figure 1 shows a clear PM_{2.5} pollution-gradient for poor general health, disability and all eleven of the domain-specific health outcomes and conditions, with higher proportions reporting ill health, disability or the presence of a long-term condition in the higher pollution quintiles in all cases. While such variation in the levels of ill-health across exposure quintiles may in part reflect the causal impact of pollution, however, it will also reflect the combined effects of all other relevant differences between those who lived in high pollution areas and those who lived in low pollution areas. For example, individuals in our sample who lived in more polluted areas between 2002 and 2010 were more likely to live in social housing in 2001, a characteristic which on its own also predicts worse health in 2011. This motivates our multivariate regression analysis.

Figure 1: Means of Health Outcomes by PM_{2.5} Exposure Quintile



Notes: Plot shows the proportion of the analysis sample reporting a particular health problem by quintile of PM_{2.5} exposure. 95% confidence intervals also displayed.

Table 4 shows the estimated effects on poor general health, disability and each of the eleven domain-specific health outcomes of exposure to a higher average PM_{2.5} level by 5 $\mu\text{g}/\text{m}^3$, first with no conditioning on observable characteristics (Model 1), then when conditioned on the full set of observable individual and household characteristics listed in Table 3 (Model 2), and finally when conditioned on the full set of observable individual and household characteristics listed in Table 3 along with neighbourhood dummies for area of residence in 2011 (Model 3). Full results for Model 3 are presented in the Supplementary Material.

Table 4: Effects of PM_{2.5} Exposure on Self-Reported Health in 2011

	(1) Unconditional	(2) (1) + Individual and Household Controls	(3) (2) + 2011 Neighbourhood FE
Poor General Health	0.0561*** [0.0402,0.0720]	0.0246*** [0.0181,0.0311]	0.0206*** [0.0093,0.0320]
LTAL Illness	0.0641*** [0.0413,0.0870]	0.0137*** [0.0057,0.0216]	0.0087 [-0.0047,0.0221]
Other Condition	0.0170*** [0.0118,0.0223]	0.0086*** [0.0042,0.0129]	0.0017 [-0.0090,0.0123]
Blindness	0.0088*** [0.0060,0.0116]	0.0014 [-0.0008,0.0035]	0.0028 [-0.0025,0.0081]
Communication Difficulties	0.0043*** [0.0019,0.0068]	-0.0009 [-0.0027,0.0010]	0.0001 [-0.0050,0.0053]
Mobility Difficulties	0.0624*** [0.0445,0.0804]	0.0188*** [0.0114,0.0261]	0.0235*** [0.0099,0.0370]
Learning Difficulties	0.0037** [0.0009,0.0065]	-0.0011 [-0.0032,0.0010]	-0.0062* [-0.0114,-0.0011]
Mental Health	0.0430*** [0.0308,0.0552]	0.0152*** [0.0101,0.0203]	0.0092 [-0.0027,0.0211]
Long-Term Pain	0.0508*** [0.0351,0.0664]	0.0169*** [0.0093,0.0244]	0.0149* [0.0010,0.0287]
Breathing Difficulties	0.0558*** [0.0439,0.0676]	0.0296*** [0.0237,0.0356]	0.0173** [0.0052,0.0295]
Memory Loss	0.0151*** [0.0106,0.0197]	0.0042** [0.0014,0.0070]	0.0024 [-0.0042,0.0090]
Chronic Illness	0.0338*** [0.0273,0.0404]	0.0168*** [0.0121,0.0215]	0.0183** [0.0071,0.0295]
Deafness	0.0190*** [0.0139,0.0241]	0.0102*** [0.0060,0.0144]	0.0145** [0.0046,0.0244]
Observations	220166	220166	220166
Controls	No	Yes	Yes
2011 Neighborhood FE	No	No	Yes

Note: Each model is an LPM with standard errors clustered by 2011 Ward. Each cell contains a linear regression coefficient (showing the effect of a 5 µg/m³ increase) and 95% confidence interval from a single model. The pollution variable represents the mean pollution exposure level between 2002 and 2010. Control variables (all measured in 2001): Age group, gender, country of birth, economic status, highest education level, religion, marital status; household family type, household no. of dependent children, household no. of cars, household tenure, and activity-limiting disability and general health in 2001. Neighbourhood fixed effects (Ward dummies) are for residential neighbourhood in 2011 (Model 3). The coefficients on all variables for Model 3, except Ward dummies, are reported in the corresponding table in the Supplementary Material. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

The estimates from Model 1 – unadjusted estimates showing the unconditional associations between long-term exposure to PM_{2.5} and health outcomes – reflect the pattern from Figure 1: self-rated general health, disability and all eleven domain-specific health outcomes in 2011 are worse for those exposed to higher levels of pollution over the long term, and substantially so. Estimated linear regression coefficients on the exposure variable range from .0037 to .0641, and all are statistically significant with $p < 0.001$, except learning difficulties for which $p < 0.01$. In semi-elasticity terms these effect sizes range from 25% (deafness, other health conditions) to 70% (poor general health, memory loss).

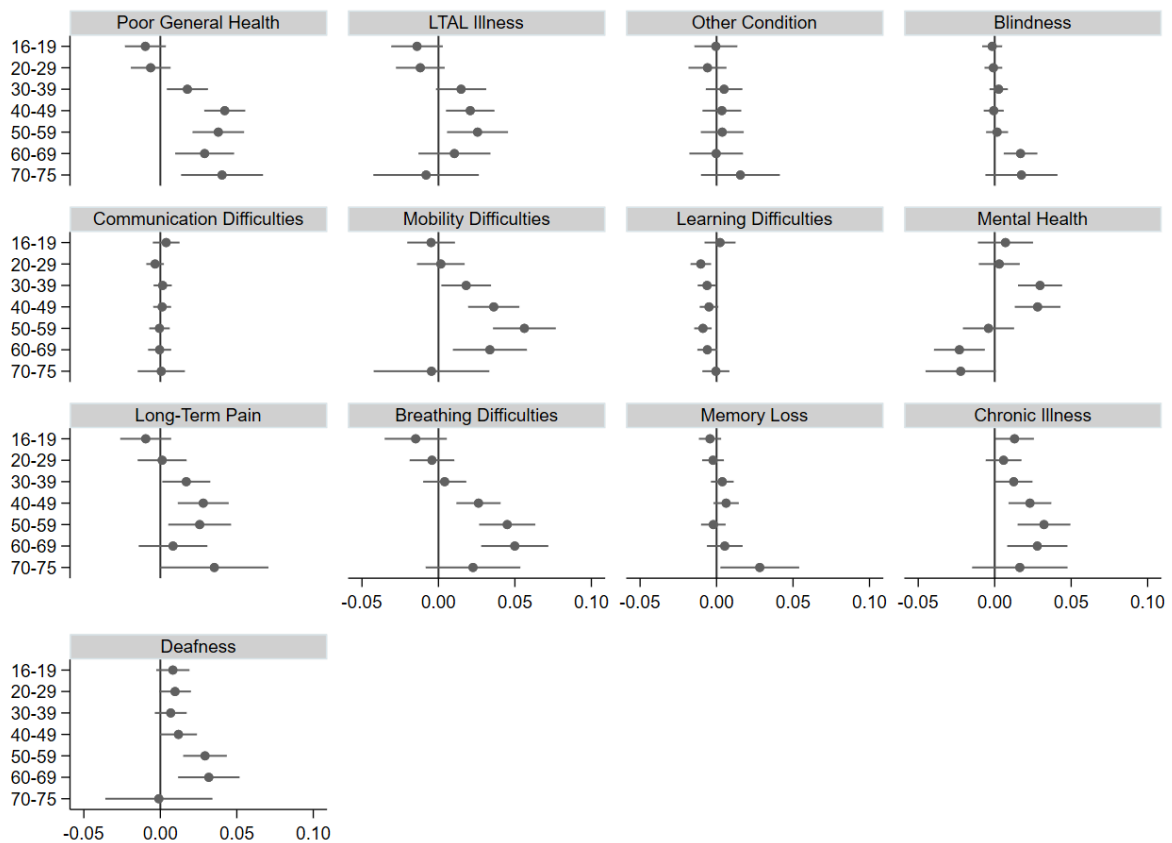
Turning to Model 2, while some of these associations are qualitatively sensitive to adjusting for individual and household level observables – this is the case for blindness, communication difficulties, and learning difficulties – positive, statistically significant and non-trivial magnitude coefficients persist for poor general health, disability and the other domain-specific outcomes, in most cases at the $p < 0.001$ level. Coefficient magnitudes fall substantially, however, with the largest effects, in semi-elasticity terms, now for poor general health (at 30%) and for breathing difficulties (at 28%).

The final column in Table 4 reports estimates from Model 3, which extends Model 2 by inclusion of 2011 neighbourhood fixed effects. Estimated magnitudes are further attenuated in most cases and confidence intervals are typically around twice as wide as for Model 2, resulting in associations with disability and a further three domain-specific outcomes that are no longer positive and statistically significant at conventional levels. Nevertheless, the association between long-term exposure to PM_{2.5} and poor general health is qualitatively robust, remaining positive, substantial in magnitude (linear regression coefficient .021, semi-elasticity 25%), with $p\text{-value} < 0.001$. This effect is similar in magnitude to the estimated difference between those aged 26-29 years and those aged 40-49 years in 2011. The following domain-specific health outcome estimates are also qualitatively robust to adjustment for neighbourhood fixed effects alongside other observed controls: mobility difficulties, long-term pain, breathing difficulties, chronic illness, and deafness, with linear regression coefficients (semi-elasticities) of .024 (14%, $p < 0.001$), .015 (9%, $p < 0.05$), .017 (17%, $p < 0.01$), .018 (18%, $p < 0.01$), and .015 (20%, $p < 0.01$) respectively. For breathing difficulties, for example, the estimated effect size is between the effect sizes of being 50-59 compared to 26-29 and being 60-69 compared to 26-29 in 2011. Note that, with the exception of long-term pain, all of these domain-specific associations would remain statistically significant (with at least $p < 0.1$) even after a conservative Bonferroni correction for multiple outcomes (e.g., Ottenbacher, 1998). Of the seven outcomes for which statistically significant and positive associations do not survive

conditioning on individual and household characteristics together with neighbourhood fixed effects, the largest-magnitude (but imprecisely-) estimated effects in semi-elasticity terms are for blindness (15%), poor mental health (12%), and memory loss (11%).

Our sample coverage, both in terms of size and representativeness, allows us to go beyond average effects to examine whether associations between health outcomes and long-term exposure to ambient PM_{2.5} vary by demographic factors such as age and gender, by socio-economic factors such as household tenure prior to the exposure period, and by prior health. We do so by re-estimating Model 3 including interactives between pollution exposure and our age categories, and (separately in each case) gender, prior health, and 2001 household tenure. The resulting estimates are summarized in Figures 2-6.

Figure 2: Health Effects of Long-term PM_{2.5} Exposure, by 2001 Age Group

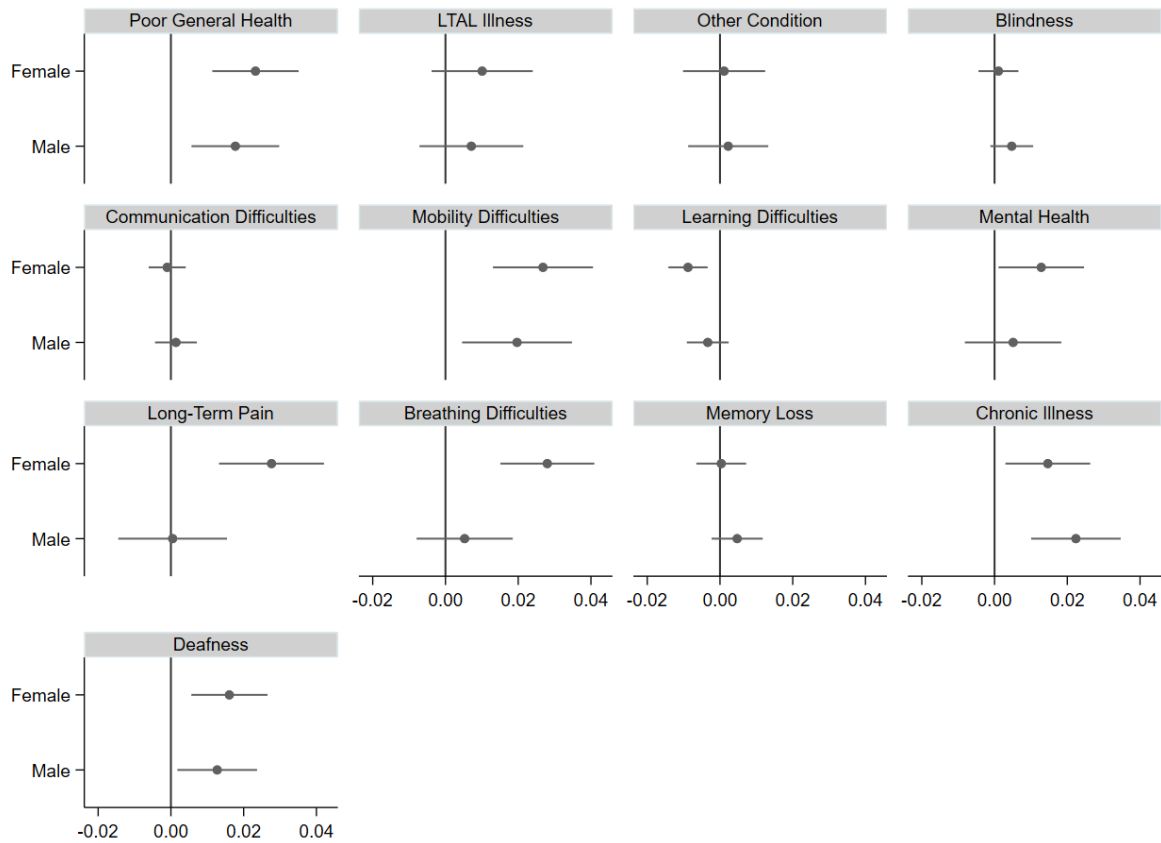


Notes: Plot shows the effect of a 5 µg/m³ increase in PM_{2.5} exposure by age group along with 95% confidence intervals. The coefficients were obtained by estimating Model 3 with interaction terms between the PM_{2.5} variable and age group. Estimation was performed separately by outcome.

Figure 2 shows that all six outcomes with statistically significant average associations with PM_{2.5} exposure in Model 3, including poor general health, display a broadly similar age-related

pattern, with zero association among younger age groups (aged <30 years or <40 years in 2011, depending on outcome) and for some domain-specific outcomes (but not poor general health) also for the oldest age group (80+ years in 2011). Also, some outcomes with statistically insignificant associations on average show positive and statistically significant associations for specific age groups, including the oldest age group for memory loss.

Figure 3: Health Effects of Long-term PM_{2.5} Exposure, by Gender

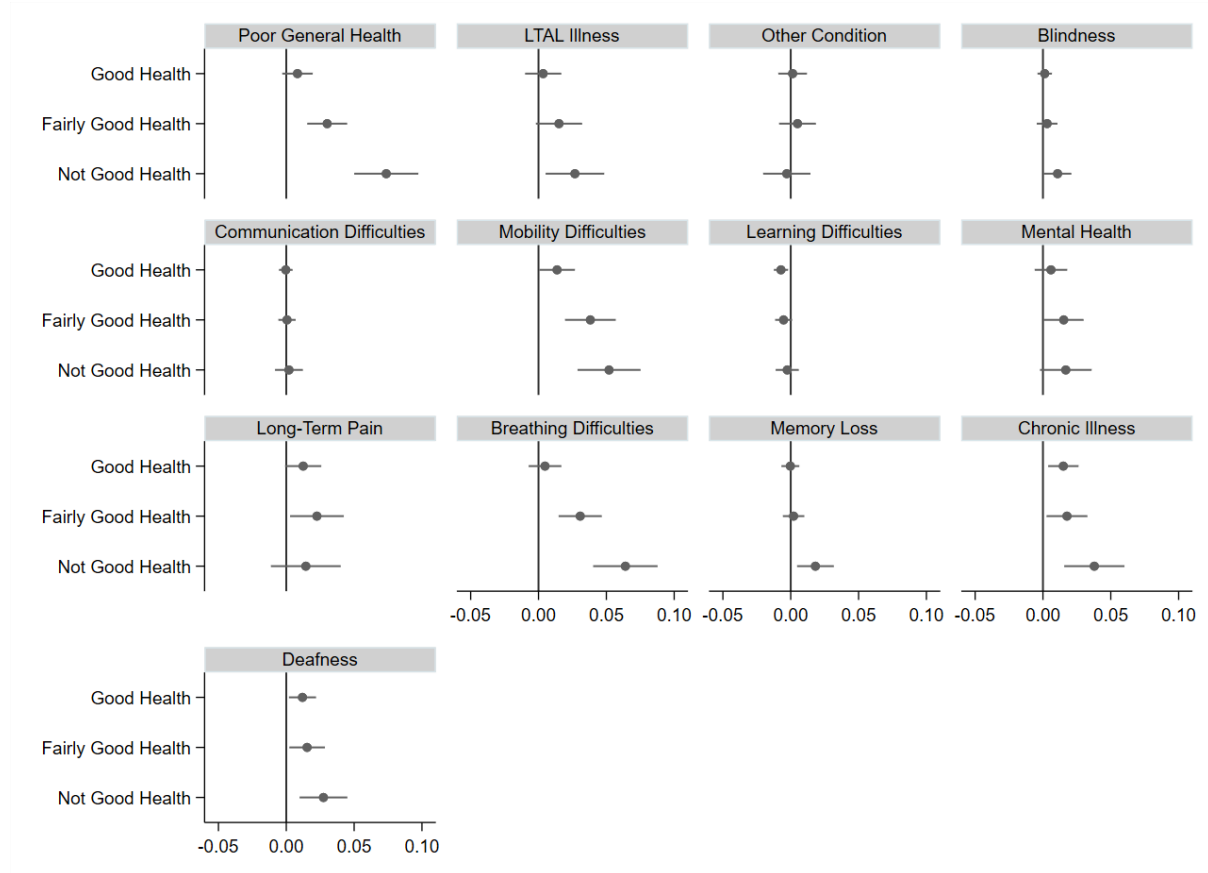


Notes: Plot shows the effect of a 5 µg/m³ increase in PM_{2.5} exposure by gender along with 95% confidence intervals. The coefficients were obtained by estimating Model 3 with interaction terms between the PM_{2.5} variable and gender. Estimation was performed separately by outcome.

Figure 3 shows that PM_{2.5} associations do not vary significantly by gender, although estimated associations for long-term pain and mental ill health are statistically significant for females but not for males. Figures 4 and 5 show that outcomes for which associations are positive and statistically significant on average tend to show stronger associations for those with poor prior general health or a prior long-term activity limitation. Again, there are outcomes with no significant association on average that nevertheless show a statistically significant association for one or more specific group, including memory loss and blindness

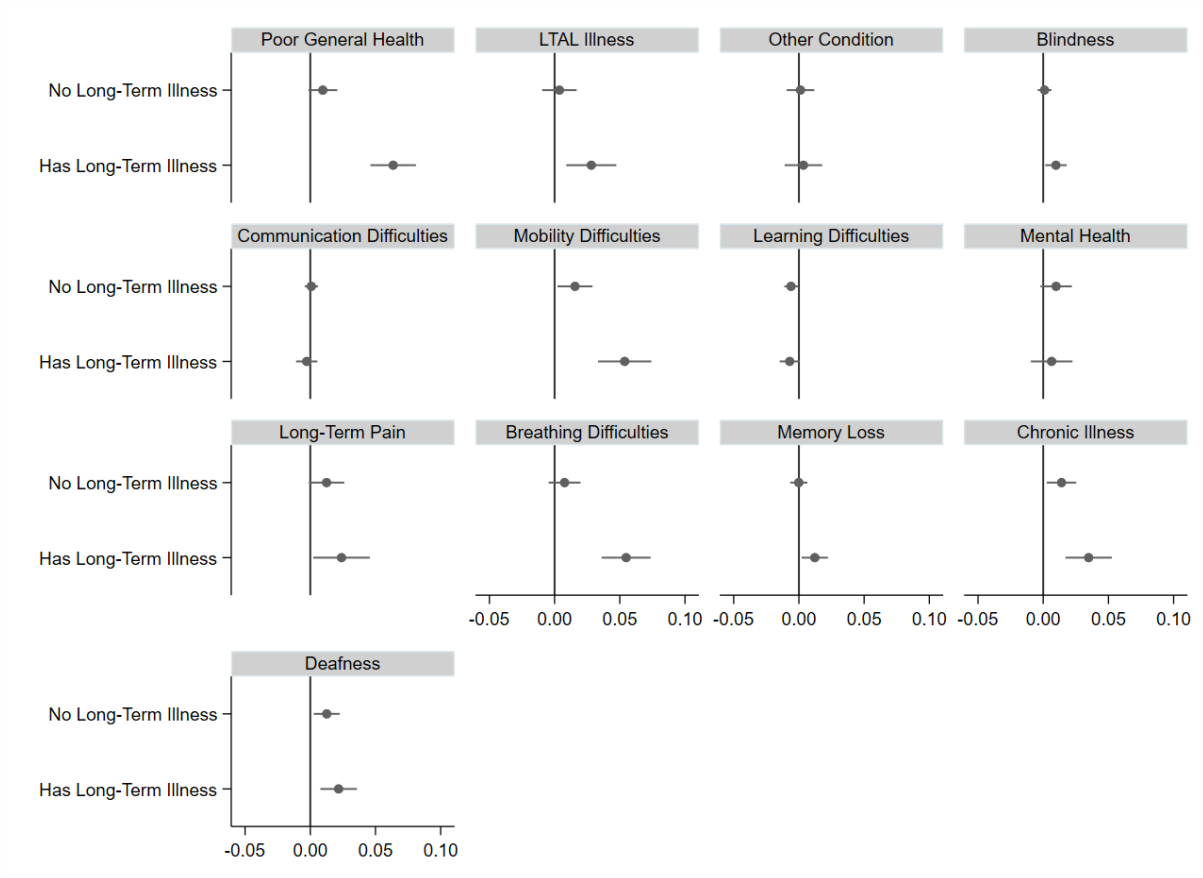
for those with a prior long-term activity-limitation or poor prior general health. Figure 6 shows no significant differences in associations with PM_{2.5} exposure by prior household tenure.

Figure 4: Health Effects of Long-term PM_{2.5} Exposure, by Prior General Health



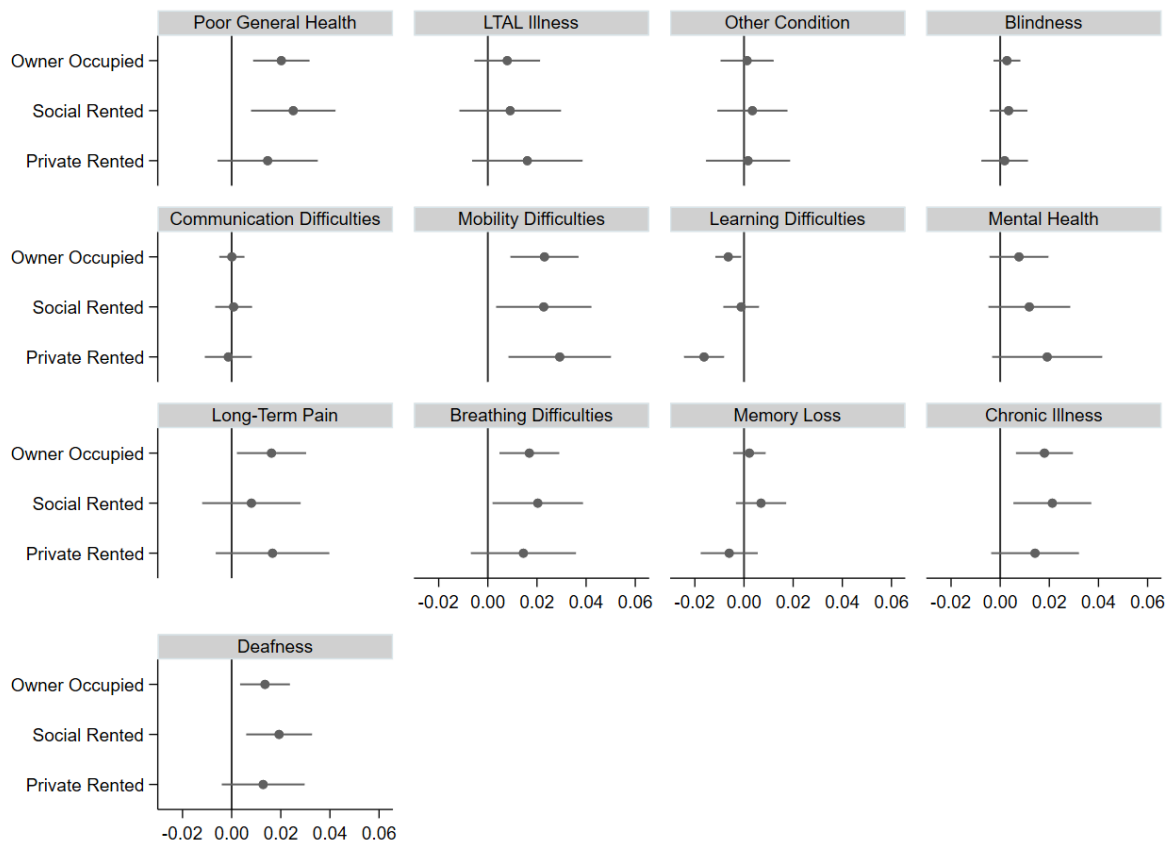
Notes: Plot shows the effect of a 5 µg/m³ increase in PM_{2.5} exposure by prior general health along with 95% confidence intervals. The coefficients were obtained by estimating Model 3 with interaction terms between the PM_{2.5} variable and prior general health. Estimation was performed separately by outcome.

Figure 5: Health Effects of Long-term PM_{2.5} Exposure, by Prior Activity-Limiting Disability



Notes: Plot shows the effect of a 5 µg/m³ increase in PM_{2.5} exposure by prior long-term activity-limiting illness along with 95% confidence intervals. The coefficients were obtained by estimating Model 3 with interaction terms between the PM_{2.5} variable and prior long-term activity-limiting illness. Estimation was performed separately by outcome.

Figure 6: Health Effects of Long-term PM_{2.5} Exposure, by Prior Household Tenure



Notes: Plot shows the effect of a 5 µg/m³ increase in PM_{2.5} exposure by household tenure along with 95% confidence intervals. The coefficients were obtained by estimating Model 3 with interaction terms between the PM_{2.5} variable and household tenure. Estimation was performed separately by outcome.

Returning to average effects at the level of the whole sample, although our preferred model conditions extensively on observed individual and household characteristics and 2011 neighbourhood fixed effects, potentially relevant but unobserved differences could remain between those with higher long-term pollution exposures and those with lower long-term pollution exposures which could confound our estimates. Table 5 presents key estimates from our two sensitivity analyses designed to explore this concern. The first column of estimates (column 2) reproduces those for Model 3 in Table 4. The next two columns give key estimates from the Oster-style analysis which uses the degree of selection on observed covariates in Model 3 (once the data are demeaned by the 2011 neighbourhood fixed effects) to inform scenarios about the potential for selection on unobserved confounders. Specifically, column 3 reports bias-adjusted linear regression coefficients which assume selection on unobservables is proportional to selection on observables. One tentative interpretation of these estimates is that they represent possible lower bounds on causal effects of PM_{2.5} exposure on the relevant outcomes where selection biases estimates upwards, although with observational data in this

context we are wary of this interpretation. Column 4 reports the degree of selection on remaining unobservables which would be required to generate an estimated PM_{2.5} effect of zero. The lower the degree of selection required to ‘kill’ the coefficient, the more likely it is that it is explained by remaining confounders rather than by a possible causal impact of ambient air pollution, with $\delta=1$ (proportional selection on observed and unobserved characteristics) again considered a reasonable threshold in the literature that adopts a similar approach. The final column in Table 5 presents estimates from the extended neighbourhood fixed effects model including year-specific neighbourhood fixed effects throughout the exposure period.

First consider the bias-adjusted estimated associations in column 3. Overall, these suggest the Model 3 estimates presented in Table 4 are reassuringly robust to the possible confounding effects of unobserved characteristics. Poor general health remains positively and statistically significantly associated with PM_{2.5} exposure, as do mobility difficulties, chronic illness, and deafness. Magnitudes are further attenuated for poor general health and mobility difficulties but not for chronic illness and deafness. Further, if one accepts the lower bound interpretation of these estimates, then the suggestion is that long-term exposure to PM_{2.5} that is higher by 5 $\mu\text{g}/\text{m}^3$ on average increases the proportion of the population reporting poor general health by *at least* 1.3pp (semi-elasticity 17%). The equivalent estimated effects for mobility difficulties, chronic illness and deafness are 1.7pp (10%), 1.8pp (18%), and 1.5pp (20%), respectively. The estimated lower-bound PM_{2.5} effect on reporting long-term breathing difficulties falls just outside conventional levels of statistical significance but remains large in magnitude, tentatively suggesting a marginally statistically significant impact of at least 1.2pp (11%). The estimated lower-bound PM_{2.5} effect on reporting long-term pain falls further outside conventional levels of statistical significance, falls in magnitude, and is the least robust of the six health outcomes in this scenario. Also note the lack of evidence here to overturn the conclusion of no PM_{2.5} effects, at least on average, for any of the other seven health outcomes and conditions. The column 4 estimates support this conclusion of overall robustness, again with the most likely exception being long-term pain. Specifically, the degree of selection on unobservables required to explain away the Model 3 coefficient for poor general health significantly exceeds one, as is the case for mobility difficulties and breathing difficulties. In contrast, for long-term pain and the seven health outcomes which appear unrelated to PM_{2.5} exposure in Model 3, estimated δ s do not significantly exceed one. Note that we ignore estimated δ s for chronic illness and deafness because selection on unobservables does not attenuate estimated associations with PM_{2.5}.

Table 5: Sensitivity to Selection Bias: Model 3 Oster Analysis and Model 4 (Neighborhood*Year Fixed Effects Model)

	β	β^*	δ^*	Model 4
Poor General Health	0.0206*** [0.0093,0.0320]	0.0134** [0.0032,0.0235]	2.81* [1.12,4.51]	0.0149 [-0.0041,0.0339]
LTAL Illness	0.0087 [-0.0047,0.0221]	-0.0022 [-0.0148,0.0104]	0.80 [-0.28,1.87]	-0.0001 [-0.0230,0.0229]
Other Condition	0.0017 [-0.0090,0.0123]	0.0010 [-0.0095,0.0116]	2.65 [-56.51,61.81]	0.0026 [-0.0147,0.0199]
Blindness	0.0028 [-0.0025,0.0081]	0.0013 [-0.0038,0.0065]	1.92 [-2.05,5.88]	0.0084 [-0.0017,0.0185]
Communication Diff.	0.0001 [-0.0050,0.0052]	-0.0017 [-0.0069,0.0036]	0.06 [-2.96,3.09]	0.0031 [-0.0042,0.0105]
Mobility Difficulties	0.0235*** [0.0099,0.0370]	0.0167** [0.0046,0.0289]	3.44* [1.29,5.59]	0.0262* [0.0032,0.0492]
Learning Difficulties	-0.0062* [-0.0114,-0.0011]	-0.0088** [-0.0142,-0.0033]	-2.51 [-4.90,-0.12]	-0.0033 [-0.0110,0.0045]
Mental Health	0.0092 [-0.0027,0.0211]	0.0004 [-0.0115,0.0123]	1.04 [-0.36,2.44]	0.0134 [-0.0035,0.0304]
Long-Term Pain	0.0149* [0.0010,0.0287]	0.0106 [-0.0042,0.0253]	3.42 [-0.12,6.97]	0.0162 [-0.0082,0.0406]
Breathing Difficulties	0.0173** [0.0052,0.0294]	0.0118 [-0.0004,0.0240]	3.10* [0.67,5.53]	0.0244* [0.0024,0.0463]
Memory Loss	0.0024 [-0.0042,0.0090]	-0.0000 [-0.0070,0.0069]	0.99 [-2.31,4.29]	0.0008 [-0.0091,0.0108]
Chronic Illness	0.0183** [0.0071,0.0295]	0.0183*** [0.0083,0.0283]	314.40 [-1039.69,1668.48]	0.0274** [0.0070,0.0478]
Deafness	0.0145** [0.0046,0.0244]	0.0166*** [0.0076,0.0256]	-7.17 [-13.48,-0.86]	0.0125 [-0.0043,0.0293]
Observations	220166	220166	220166	220166

Notes: In column 2, β is the estimated pollution linear regression coefficient in Model 3 with 95% confidence intervals in brackets (calculated using 2011-ward clustered standard errors). In column 3, β^* is the (Oster) bias-adjusted pollution coefficient assuming proportional selection on observables and unobservables (δ equals 1). In column 4, δ^* is the degree of selection on unobservables required to generate a pollution coefficient of 0; the stars apply to a test of delta greater than or equal to 1. These (column 3 and 4) parameters assume a maximum R-squared value of 1.3 times the model 3 R-squared, following Oster (2019), with bootstrapped standard errors (with 100 replications) clustered by 2011 Ward displayed in parentheses. Column 5 shows estimated β s (linear regression coefficients) and 95% confidence intervals (calculated using 2011-ward clustered standard errors) for Model 4 including the full set of ward*year dummies for the period 2001-2011. Statistical significance level: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

The final column of Table 5, including the full set of year-specific neighbourhood fixed effects (Model 4), provides additional evidence on the robustness of the Model 3 estimates, albeit only tentatively so given the substantially increased confidence intervals. For poor general health, the Model 4 linear regression coefficient falls between the estimated Model 3 coefficient in column 2 and the estimated bias-adjusted lower-bound coefficient in column 3 of Table 5. Of the five domain-specific health outcomes where associations survived conditioning on individual, household and 2011 neighbourhood fixed effects in Model 3, only for deafness is the Model 4 linear regression coefficient *below* the estimated lower-bound coefficient in Column 3. For the other four domain-specific health outcomes the Model 4 linear regression coefficients are larger in magnitude than the corresponding Model 3 coefficients, although only for mobility difficulties, breathing difficulties and chronic illness are these estimates sufficiently precise so as to be statistically significant at conventional levels.

Equivalent (Model 3) estimates for long-term exposure to NO₂ and SO₂, similarly estimated as single pollutant models, are presented in the Supplementary Material. The pattern (and normalized magnitudes of effects) is broadly similar, with statistically significant, positive and non-trivial magnitude estimated effects of pollution exposure for poor general health, mobility difficulties, long-term pain (NO₂ only), breathing difficulties (SO₂ only), chronic illness, and deafness (NO₂ only), with zeroes otherwise.

Discussion

This study exploits longitudinal data tracking exposure to ambient PM_{2.5} for a large representative sample of the Northern Ireland population between the 2001 and 2011 Censuses. These data offer a unique opportunity to study the health effects of genuinely long-term exposure to ambient air pollution on self-rated general health, disability and across a wide range of domain-specific self-reported health measures, both on average and distinguishing between different demographic and socio-economic groups, with a high degree of statistical control for potentially confounding factors. Robustness to the presence of omitted potential confounders is assessed via two extensions. In each of these respects the study makes a significant contribution to the international literature on the health effects of long-term exposure to ambient air pollution.

First consider self-rated general health, for which we find a highly robust association, with those exposed to higher long-run levels of ambient PM_{2.5} pollution substantially more likely to report poor general health even after extensive conditioning on individual and household

characteristics and neighbourhood fixed effects. This is consistent with earlier evidence suggesting a positive conditional association between PM_{2.5} exposure and self-reported poor general health (Klompaker et al., 2019). The current study builds on existing evidence, however, by demonstrating the robustness of this association to sensitivity analyses designed to explore the potential for biases stemming from unobserved confounders.

Similarly, for five of the eleven domain-specific health outcomes considered here – mobility difficulties, long-term pain, breathing difficulties, chronic illness, and deafness – our main neighbourhood fixed effects model generates positive, statistically significant and non-trivial magnitude estimates. All but the association for long-term pain are qualitatively robust to sensitivity analyses including adjustment for multiple hypothesis testing, Oster-style assessment of sensitivity to selection on unobservables, and conditioning on neighbourhood*year fixed effects for the whole exposure period. These estimated associations are also qualitatively consistent with earlier studies suggesting a positive conditional association between PM_{2.5} exposure and respiratory ill health (Xing et al., 2016; Kim et al., 2017; Singh et al., 2023); cardiovascular disease (Brook et al., 2010); other types of chronic illness including conditions potentially linked to mobility difficulties and/or long-term pain such as rheumatoid arthritis and diabetes (Bowe et al., 2018; Adami et al., 2022; Kim et al., 2017); and hearing loss (Tsai et al., 2021).

For chronic illness and breathing difficulties, the robustness of these estimates to both observed and unobserved confounders is consistent with the assessment of EPA (2019) that long-term exposure to ambient PM_{2.5} has a causal effect on cardiovascular disease and a likely-to-be-causal effect on respiratory ill health. The robust association between mobility difficulties and PM_{2.5} exposure may also reflect, in part, biological mechanisms acting through cardiovascular, respiratory and other chronic illnesses. Note that among the eleven domain-specific health outcomes considered here, reporting mobility difficulties was most strongly correlated with reporting breathing difficulties ($\rho=0.28$) and reporting chronic illness ($\rho=0.25$), for which biological mechanisms are not in doubt. Biological mechanisms for a causal link between PM_{2.5} exposure and deafness have been less extensively researched but are difficult to rule out *ex ante*.

Next consider the other domain-specific health outcomes and conditions, along with self-reported disability, where our model suggests unconditional associations can be explained by confounders. For long-term activity-limiting disability, our result is consistent with an earlier study which found no effects at PM_{2.5} concentrations like those experienced in Northern Ireland (Lv et al., 2020). For blindness, there is some contrasting evidence in the literature of a

statistically significant conditional association between PM_{2.5} and glaucoma (Chua et al., 2019), and Canadian evidence of a borderline statistically significant association between PM_{2.5} and a broader measure of ocular health, closer to the Census measure we used here, that *strengthens* upon conditioning (Grant et al., 2021). We found no existing studies showing a conditional association between long-term (adult) PM_{2.5} exposure and either learning difficulties or communication difficulties. For poor mental health, however, there is existing UK evidence of an association with PM_{2.5} exposure that survives extensive conditioning, albeit for residents of an area of south London with considerably higher ambient PM_{2.5} levels than those experienced by our Northern Ireland sample (Bakolis et al., 2021), with a recent review assessing the air pollution and mental health literature overall as inconclusive (Ventriglio et al., 2021).

Finally, there is an extensive literature presenting evidence of a conditional association between PM_{2.5} exposure and cognitive decline among older adults (Paul et al., 2019; Peters et al., 2019; Power et al., 2016). Although there are studies that report no conditional association (Cullen et al., 2018), the weight of evidence in this literature suggests such an association exists, although estimated magnitudes (and the extent of conditioning) vary widely. At first glance our own estimates, suggesting no conditional association on average, appear out of step with this literature. We do find evidence suggesting PM_{2.5} exposure predicts memory loss for particular groups, however, including the over-80s and those with prior poor health or long-term activity-limiting health conditions, which can help to partly reconcile our estimates with this literature. Most of the air pollution and dementia literature restricts samples to older age groups. Some studies also find higher dementia risk from long-term PM_{2.5} exposure for those with pre-existing health conditions (e.g., Grande et al., 2020).

This study has potential implications for policy within Northern Ireland, as well as at the UK and international levels. Starting with the most general, although we are not able to quantify causal effects of long-term exposure to PM_{2.5} (or, to the extent that it is correlated, ambient air pollution more generally) in this study, one tentative interpretation of the Oster-style estimates presented here is that they provide lower bounds for such causal effects for self-rated general health and several domain-specific health outcomes including chronic illness. This suggests that interventions to reduce long-term exposure to ambient PM_{2.5}, at the levels typical of Northern Ireland, could improve population health in several overlapping respects. Because ambient PM_{2.5} levels are associated with many dimensions of social disadvantage which are themselves associated with health outcomes, such interventions may also help to reduce existing health inequalities, over and above measures to tackle underlying social deprivation

and social inequalities. For policy makers within Northern Ireland, this study presents the first ever region-specific direct evidence of detrimental morbidity effects of ambient PM_{2.5} air pollution at the population level and is particularly timely given recent moves towards introducing a new Northern Ireland Clean Air Strategy. Indeed, our estimates suggest that existing reductions in population-weighted average exposures to ambient PM_{2.5} since the 2002-2011 period in Northern Ireland will likely have reduced morbidity below levels that might otherwise have been experienced. Nevertheless, latest available estimates suggest that many in Northern Ireland continue to be exposed to ambient PM_{2.5} levels well above the 2021 WHO AQG, suggesting an opportunity for further reductions in PM_{2.5} levels to further reduce morbidity.

Recall that we estimate a single pollutant model here, so we cannot rule out that estimated PM_{2.5} effects also capture the impacts of other correlated pollutants to some extent. A further limitation of this study is that looking beyond self-rated general health to multiple domain-specific outcomes increases the risk of Type 1 error, i.e., that some estimates are statistically significant purely by chance when using conventional hypothesis testing procedures. However, our interpretation of estimated associations as meaningful is supported by the fact that significant associations were found where existing evidence and biological plausibility is most compelling (e.g., for chronic illness and breathing difficulties) and not where such evidence and biological plausibility is least compelling (e.g., for learning difficulties), together with the robustness of key estimates to extensive sensitivity analysis including conservative adjustment for multiple outcomes. As new data become available it may be possible to address at least some of the other constraints faced by this study in further research. As data linking the 2021 Census to these earlier Censuses and points in between become available, more up to date estimates, at generally lower levels of pollution given recent trends, will be possible. Further, the 2021 Census link will offer the chance to study exposure impacts over a 20-year period, with multiple domain-specific health outcomes observed in both 2011 and 2021.

Conclusions

This study's contribution is to examine extensively-conditioned and genuinely *long-run* pollution effects across a comprehensive range of self-reported health measures in nationally representative data. We present evidence that higher long-term exposure to ambient PM_{2.5} is conditionally associated with the probability of reporting poor general health and several long-term health conditions, including chronic illness. We also show that these associations are

robust to the likely confounding effects of unobservables under plausible assumptions. These results underscore the urgency of reducing population-wide exposure to PM_{2.5} because they indicate that doing so may contribute to improvements in population health, including in conditions less commonly considered in the existing literature.

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Appendix: Supplementary Material

Further information about the sample and robustness checks

NILS data

Our sample excludes those with partial address records (30,134) or address records that are inconsistent between NILES tables (2,310) but who are nevertheless returned in both the 2001 and 2011 Censuses. Conclusions are robust to re-estimation including these individuals in the sample with pollution exposures averaged over available exposure periods (see Figures SM4 and SM5). Our sample also includes individuals where missing values were imputed in the Census data made available to researchers. The few remaining missing values are cases where imputation was not possible. This is the case for 892 individuals who we drop from our analysis sample.

Census and pollution data

We do not include annual average pollution data for 2011 because the 2011 Census collected information on the 27th March 2011. PM_{2.5} data are not available for 2001. For a time series of population-weighted PM_{2.5} exposure in Northern Ireland from 2002-2019 see https://qrap.connect.qub.ac.uk/Air_Pollution_Dashboard_Northern_Ireland/.

Neighbourhood dummies

Neighbourhood dummies are specified at the electoral ward level. Electoral wards are fine-grained administrative geographies used for electing local government councillors, containing roughly 3,000 residents on average. 1x1km grid squares in Northern Ireland contain approximately 120 residents on average.

Sensitivity to definitions of health outcomes

We examine sensitivity to including ‘fair’ along with ‘bad’ and ‘very bad’ rather than with ‘good’ and ‘very good’ in our measure of self-rated general health. The conclusions remain the same regardless of definition used, though there are minor differences in the point estimates. We also examine sensitivity to merging the two ‘limited’ categories into a single limited a lot / a little category in our measure of self-reported disability. Once again, the conclusions are no different when this definition is used (see Figures SM2 and SM3).

2001 health measures

In 2001, subjective general health was recorded on a 3-point rather than a 5-point scale, and respondents were only able to record whether they were activity-limiting disabled or not, with no distinction possible between those limited a lot and those limited a little.

Results: bias adjusted coefficients for chronic illness and deafness

Although many individual and household characteristics are significantly associated with chronic illness after conditioning on 2011 neighbourhood fixed effects, their net effect on the estimated association with PM_{2.5} exposure is close to zero (their effects balanced out). Hence the bias-adjusted coefficient is very close to the original Model 3 coefficient. For deafness the net effect of selection on observable individual and household characteristics, once neighbourhood fixed effects are conditioned upon, is positive. Hence the bias-adjusted coefficient is slightly larger in magnitude than the Model 3 coefficient.

Results: seemingly-unrelated regression

A seemingly-unrelated regression (SUR) version of Model 3, estimated simultaneously on all outcomes to account for correlation of residuals across outcomes, gives very similar estimated confidence intervals.

Results: Bonferroni correction

Views on whether to adjust statistically for multiple hypothesis testing, and if so how, differ. We make no such adjustments in the estimates presented in the paper. However, with 11 domain-specific health outcomes it is difficult to rule out Type 1 error as an explanation for one or more of the statistically significant associations presented in the main text. We therefore check the sensitivity of the conclusions we draw from Model 3 to such an adjustment. Estimated associations with chronic illness, mobility difficulties and deafness remain statistically significant at the 95% level or better, even after implementing a Bonferroni correction (a simple but very conservative way of addressing multiple comparisons concerns). This is not the case for long-term pain, with the estimated association falling short of statistical significance at conventional levels post-correction. For breathing difficulties the estimated association is statistically significant at the 90% level post-correction.

Table SM1: Representativeness of the Analysis Sample: Sample Means of Outcome Variables

Health Outcome	Analysis Sample	Full 2011 Sample
Poor General Health	0.081	0.080
Long-Term Limiting Illness	0.162	0.158
Other Health Condition	0.069	0.067
Blindness or Partial Sight Loss	0.019	0.019
Communication Difficulty	0.013	0.014
Mobility or Dexterity Difficulty	0.165	0.159
Learning, Intellectual or Social/Behavioural Difficulty	0.012	0.013
Emotional, Psychological or Mental Health Condition	0.080	0.082
Long-term Pain or Discomfort	0.157	0.151
Shortness of Breath or Difficulty Breathing	0.104	0.100
Frequent Confusion or Memory Loss	0.022	0.023
Chronic Illness	0.099	0.094
Deafness or Partial Hearing Loss	0.072	0.068
Observations	220166	288451

Notes: Table reports the proportion of each sample reporting each health outcome in 2011. The analysis sample is restricted to individuals enumerated at the 2001 and 2011 census, aged 26-84 in 2011, with complete information on all variables used in the analysis. The unbalanced sample includes individuals enumerated in 2011 (regardless of 2001 status), aged 26-84, with complete information on all variables displayed above.

Table SM2: Representativeness of Analysis Sample: Sample Means of 2011 Individual, Household and Neighbourhood Characteristics

	Analysis Sample	Full 2011 Sample
Female	0.536	0.525
Male	0.464	0.475
Aged 26-29 in 2011	0.070	0.076
30-39	0.170	0.196
40-49	0.233	0.234
50-59	0.211	0.199
60-69	0.175	0.164
70-79	0.110	0.101
80-84	0.031	0.030
Born in Northern Ireland	0.925	0.881
Rest of the UK	0.041	0.052
Republic of Ireland	0.021	0.026
Born Elsewhere	0.012	0.041
No Educational Qualifications	0.325	0.316
Below Degree or Equivalent	0.431	0.436
Degree, Equivalent or above	0.244	0.249
Employed	0.472	0.477
Self-employed	0.097	0.100
Unemployed	0.032	0.036
Retired	0.241	0.223
Student	0.007	0.008
Home/Family	0.045	0.047
Long-Term Sick	0.079	0.080
Other Inactive	0.027	0.029
Never Married	0.199	0.213
Married	0.620	0.603
Sep./Divorced/Widow	0.181	0.184
Catholic	0.374	0.388
Protestant	0.429	0.395
None/Not Stated	0.132	0.150
Other Christian/Religion	0.065	0.067
0 Cars in Household	0.138	0.147
One Car	0.378	0.381
Two Cars	0.345	0.341
3+ Cars	0.138	0.132
0 Dependent Children in Household	0.654	0.640
1	0.139	0.144
2	0.130	0.135
3+ Dependent Children	0.078	0.082
SOA deprivation (MDM) 2011 (1 most deprived)	0.086	0.086
2	0.094	0.094
3	0.095	0.098
4	0.102	0.106
5	0.100	0.102
6	0.099	0.106
7	0.100	0.102
8	0.108	0.107
9	0.111	0.104
10 (least deprived)	0.106	0.096
Observations	219269	286871

Notes: Table reports the proportion of each sample reporting each characteristic in 2011. The analysis sample is restricted to individuals enumerated at the 2001 and 2011 census, aged 26-84 in 2011, with complete information on all variables used in the analysis. The unbalanced sample includes individuals enumerated in 2011 (regardless of 2001 status), aged 26-84, with complete information on all variables displayed above. Samples are smaller than for Table 1 because individuals with missing values on the above (2011) variables are additionally excluded.

Table SM3: Full Regression Results, Model 3

	Poor Gen. Health	LATL Illness	Other Condition	Blindness	Communication	Mobility Difficulties	Learning, Difficulties	Mental Health	Long-Term Pain	Breathing Difficulties	Memory Loss	Chronic Illness	Deafness
PM _{2.5}	0.021*** (0.006)	0.009 (0.007)	0.002 (0.005)	0.003 (0.003)	0.000 (0.003)	0.023*** (0.007)	-0.006* (0.003)	0.009 (0.006)	0.015* (0.007)	0.017** (0.006)	0.002 (0.003)	0.018** (0.006)	0.015** (0.005)
Gender (Ref: Female)													
Male	0.001 (0.001)	-0.003 (0.001)	-0.006*** (0.001)	0.004*** (0.001)	0.005*** (0.001)	-0.016*** (0.001)	0.005*** (0.001)	-0.014*** (0.001)	-0.021*** (0.002)	-0.006*** (0.001)	0.004*** (0.001)	0.039*** (0.001)	0.040*** (0.001)
Age Group (Ref: 16-19)													
20-29	0.011*** (0.002)	0.017*** (0.003)	0.006** (0.002)	0.003** (0.001)	0.004** (0.001)	0.011*** (0.002)	0.005** (0.002)	0.011*** (0.003)	0.006* (0.003)	-0.002 (0.003)	0.002* (0.001)	0.004* (0.002)	0.002 (0.001)
30-39	0.020*** (0.003)	0.040*** (0.003)	0.022*** (0.003)	0.006*** (0.001)	0.012*** (0.002)	0.031*** (0.003)	0.015*** (0.002)	0.027*** (0.003)	0.024*** (0.003)	0.001 (0.003)	0.006*** (0.001)	0.016*** (0.002)	0.010*** (0.002)
40-49	0.041*** (0.003)	0.068*** (0.003)	0.040*** (0.003)	0.011*** (0.001)	0.012*** (0.002)	0.070*** (0.003)	0.012*** (0.002)	0.025*** (0.004)	0.065*** (0.004)	0.013*** (0.004)	0.009*** (0.002)	0.054*** (0.003)	0.032*** (0.002)
50-59	0.026*** (0.003)	0.075*** (0.004)	0.039*** (0.003)	0.016*** (0.002)	0.006** (0.002)	0.108*** (0.004)	-0.001 (0.002)	-0.025*** (0.004)	0.083*** (0.004)	0.035*** (0.004)	0.004* (0.002)	0.108*** (0.003)	0.071*** (0.003)
60-69	0.019*** (0.004)	0.110*** (0.005)	0.032*** (0.004)	0.035*** (0.003)	0.006* (0.002)	0.166*** (0.005)	-0.010** (0.002)	-0.081*** (0.004)	0.085*** (0.005)	0.062*** (0.005)	0.016*** (0.002)	0.161*** (0.005)	0.143*** (0.004)
70-75	0.033*** (0.005)	0.214*** (0.008)	0.032*** (0.005)	0.077*** (0.004)	0.023*** (0.003)	0.291*** (0.008)	-0.012*** (0.003)	-0.093*** (0.005)	0.117*** (0.007)	0.068*** (0.007)	0.069*** (0.004)	0.167*** (0.007)	0.246*** (0.007)
COB (Ref: Northern Ireland)													
Rest of UK	-0.004 (0.003)	-0.004 (0.003)	0.006 (0.003)	-0.000 (0.001)	0.000 (0.001)	0.003 (0.003)	0.002* (0.001)	0.002 (0.003)	0.004 (0.004)	0.005 (0.003)	0.001 (0.002)	0.004 (0.003)	0.007* (0.003)
ROI	-0.003 (0.004)	-0.009 (0.005)	0.006 (0.004)	0.003 (0.002)	0.001 (0.002)	-0.010 (0.006)	0.002 (0.002)	-0.007* (0.003)	-0.003 (0.005)	-0.011* (0.005)	0.002 (0.003)	-0.006 (0.005)	0.007 (0.004)
Elsewhere	0.004 (0.004)	-0.006 (0.005)	0.006 (0.004)	0.002 (0.002)	0.002 (0.002)	0.003 (0.005)	0.001 (0.002)	-0.006 (0.004)	-0.003 (0.006)	-0.012** (0.005)	-0.004 (0.002)	-0.001 (0.005)	-0.011** (0.004)
Education (Ref: No Qualifications)													
Below Degree/Equiv.	-0.022*** (0.001)	-0.042*** (0.002)	0.002 (0.002)	-0.001 (0.001)	-0.009*** (0.001)	-0.025*** (0.002)	-0.016*** (0.001)	-0.007*** (0.002)	-0.018*** (0.002)	-0.015*** (0.002)	-0.006*** (0.001)	-0.001 (0.002)	-0.002 (0.001)
Degree/Equiv. above	-0.027*** (0.002)	-0.053*** (0.002)	0.002 (0.002)	-0.001 (0.001)	-0.009*** (0.001)	-0.039*** (0.002)	-0.016*** (0.001)	-0.016*** (0.002)	-0.039*** (0.002)	-0.017*** (0.002)	-0.007*** (0.001)	0.003 (0.002)	-0.007*** (0.002)
Economic Status (Ref: Employed)													
Self-employed	0.002 (0.002)	-0.003 (0.002)	-0.002 (0.002)	-0.001 (0.001)	0.000 (0.001)	-0.002 (0.002)	-0.000 (0.001)	0.005** (0.002)	-0.001 (0.002)	-0.006** (0.002)	-0.001 (0.001)	-0.011*** (0.002)	-0.010*** (0.002)
Unemployed	0.012*** (0.003)	0.019*** (0.004)	0.005 (0.003)	0.000 (0.001)	0.002 (0.001)	0.007 (0.004)	0.002 (0.002)	0.026*** (0.004)	0.007 (0.004)	-0.006 (0.003)	0.002 (0.002)	-0.004 (0.003)	-0.006* (0.003)
Retired	0.008* (0.003)	0.033*** (0.005)	0.003 (0.003)	0.003 (0.002)	0.006*** (0.002)	0.030*** (0.005)	0.007*** (0.001)	0.032*** (0.003)	0.015*** (0.005)	-0.007 (0.004)	0.013*** (0.002)	-0.007 (0.005)	0.013** (0.004)
Student	0.008*** (0.002)	0.012*** (0.003)	0.002 (0.002)	0.001 (0.001)	0.002 (0.001)	0.010*** (0.003)	-0.000 (0.002)	-0.005 (0.003)	0.004 (0.003)	0.011*** (0.003)	0.002* (0.001)	0.010*** (0.002)	0.002 (0.001)
Home/Family	0.008*** (0.002)	0.016*** (0.003)	0.002 (0.002)	-0.001 (0.001)	0.003** (0.001)	0.009** (0.003)	0.002* (0.001)	0.039*** (0.003)	0.012*** (0.003)	-0.002 (0.002)	0.004*** (0.001)	0.002 (0.002)	-0.003 (0.002)
Long-Term Sick	0.106*** (0.004)	0.192*** (0.005)	0.010** (0.003)	0.009*** (0.002)	0.028*** (0.002)	0.145*** (0.005)	0.030*** (0.002)	0.094*** (0.004)	0.089*** (0.005)	0.008 (0.004)	0.023*** (0.002)	0.021*** (0.004)	0.004 (0.003)
Other Inactive	0.021*** (0.004)	0.045*** (0.005)	-0.000 (0.003)	-0.000 (0.002)	0.007*** (0.002)	0.008 (0.004)	0.015*** (0.002)	0.055*** (0.004)	0.006 (0.004)	-0.009* (0.004)	0.007** (0.002)	-0.012*** (0.004)	-0.007* (0.003)
Marital Status (Ref: Never Married)													
Married	0.005* (0.002)	-0.011*** (0.003)	-0.002 (0.002)	-0.006*** (0.001)	-0.021*** (0.001)	0.004 (0.003)	-0.036*** (0.002)	-0.004 (0.002)	0.028*** (0.003)	0.004 (0.002)	0.000 (0.001)	0.006** (0.002)	0.014*** (0.002)
Sep./Divorced/Widow	0.031*** (0.003)	0.025*** (0.003)	0.004 (0.003)	-0.001 (0.001)	-0.014*** (0.001)	0.043*** (0.003)	-0.026*** (0.001)	0.017*** (0.003)	0.054*** (0.003)	0.034*** (0.003)	0.013*** (0.002)	-0.001 (0.003)	0.015*** (0.002)

Religion (Ref: Catholic)													
Protestant or Other C/R	-0.004** (0.001)	-0.009*** (0.002)	0.001 (0.002)	0.000 (0.001)	0.000 (0.001)	-0.004* (0.002)	0.001 (0.001)	-0.001 (0.002)	0.002 (0.002)	-0.003 (0.002)	-0.000 (0.001)	0.004* (0.002)	0.005*** (0.002)
None or Not Stated	0.000 (0.002)	-0.003 (0.003)	0.002 (0.002)	0.001 (0.001)	0.002 (0.001)	-0.005 (0.002)	0.002 (0.001)	0.009*** (0.002)	0.004 (0.003)	-0.003 (0.002)	0.003** (0.001)	-0.002 (0.002)	0.005* (0.002)
General Health (Ref: Good Health)													
Fairly Good Health	0.026*** (0.002)	0.050*** (0.002)	0.035*** (0.002)	0.003*** (0.001)	-0.000 (0.001)	0.059*** (0.002)	-0.002** (0.001)	0.039*** (0.002)	0.074*** (0.002)	0.046*** (0.002)	0.005*** (0.001)	0.037*** (0.002)	0.011*** (0.002)
Not Good Health	0.205*** (0.004)	0.198*** (0.004)	0.059*** (0.003)	0.004* (0.002)	-0.004* (0.002)	0.166*** (0.004)	-0.020*** (0.002)	0.106*** (0.003)	0.192*** (0.004)	0.117*** (0.004)	0.033*** (0.002)	0.086*** (0.004)	0.017*** (0.003)
LTAL Illness (Ref: None)													
Has Long-Term Illness	0.057*** (0.003)	0.190*** (0.003)	0.039*** (0.002)	0.024*** (0.002)	0.023*** (0.001)	0.176*** (0.004)	0.031*** (0.001)	0.032*** (0.003)	0.133*** (0.003)	0.068*** (0.003)	0.013*** (0.001)	0.088*** (0.003)	0.036*** (0.002)
Family Type (Ref: Married Couple)													
Cohabit Couple	-0.001 (0.003)	-0.018*** (0.003)	-0.006* (0.003)	-0.002 (0.001)	-0.010*** (0.001)	-0.009** (0.003)	-0.020*** (0.002)	0.005 (0.003)	0.011** (0.003)	-0.004 (0.003)	-0.000 (0.002)	-0.001 (0.003)	0.001 (0.002)
Lone Parent	-0.010*** (0.002)	-0.018*** (0.003)	-0.000 (0.002)	-0.005*** (0.001)	-0.004** (0.001)	-0.016*** (0.003)	-0.008*** (0.002)	0.020*** (0.003)	0.003 (0.003)	-0.012*** (0.003)	-0.003* (0.001)	0.001 (0.002)	0.006** (0.002)
One Person	-0.014*** (0.003)	-0.032*** (0.004)	-0.003 (0.003)	-0.001 (0.002)	-0.011*** (0.002)	-0.018*** (0.004)	-0.018*** (0.002)	0.003 (0.003)	-0.000 (0.004)	-0.013*** (0.003)	-0.000 (0.002)	-0.016*** (0.003)	-0.003 (0.003)
Multi-Student/Other	-0.008 (0.004)	-0.021*** (0.005)	-0.012** (0.004)	-0.005 (0.002)	-0.005* (0.003)	-0.027*** (0.005)	-0.007* (0.003)	-0.001 (0.005)	-0.012* (0.005)	-0.019*** (0.005)	-0.004 (0.003)	-0.006 (0.005)	-0.002 (0.004)
No. of Children in Household (Ref: 0)													
1	-0.001 (0.001)	-0.009*** (0.002)	-0.001 (0.002)	-0.001 (0.001)	-0.003*** (0.001)	-0.009*** (0.002)	-0.004*** (0.001)	0.001 (0.002)	-0.005* (0.002)	-0.005** (0.002)	-0.002** (0.001)	-0.005** (0.002)	-0.003 (0.001)
2	-0.007*** (0.002)	-0.017*** (0.002)	-0.006*** (0.002)	-0.002* (0.001)	-0.003*** (0.001)	-0.017*** (0.002)	-0.005*** (0.001)	-0.000 (0.002)	-0.011*** (0.002)	-0.012*** (0.002)	-0.003** (0.001)	-0.011*** (0.002)	-0.004* (0.002)
3+	-0.012*** (0.002)	-0.026*** (0.002)	-0.006** (0.002)	-0.000 (0.001)	-0.003*** (0.001)	-0.022*** (0.002)	-0.005*** (0.001)	-0.004 (0.002)	-0.016*** (0.003)	-0.014*** (0.002)	-0.003*** (0.001)	-0.012*** (0.002)	-0.002 (0.002)
No. of Cars in Household (Ref: 0)													
1	-0.008*** (0.002)	-0.013*** (0.003)	0.002 (0.002)	-0.010*** (0.001)	-0.005*** (0.001)	0.003 (0.003)	-0.007*** (0.001)	-0.023*** (0.003)	0.008** (0.003)	-0.005 (0.003)	-0.011*** (0.001)	0.004 (0.002)	0.000 (0.002)
2	-0.017*** (0.003)	-0.026*** (0.003)	0.001 (0.002)	-0.012*** (0.001)	-0.006*** (0.001)	-0.008** (0.003)	-0.007*** (0.001)	-0.031*** (0.003)	-0.000 (0.003)	-0.012*** (0.003)	-0.013*** (0.002)	-0.000 (0.003)	0.003 (0.002)
3+	-0.018*** (0.003)	-0.032*** (0.004)	0.001 (0.003)	-0.013*** (0.002)	-0.009*** (0.001)	-0.013*** (0.004)	-0.012*** (0.001)	-0.031*** (0.003)	0.004 (0.004)	-0.010** (0.003)	-0.012*** (0.002)	0.002 (0.003)	0.002 (0.003)
Household Tenure (Ref: Owner)													
Social Rented	0.037*** (0.002)	0.039*** (0.003)	0.000 (0.002)	0.001 (0.001)	-0.000 (0.001)	0.024*** (0.003)	0.001 (0.001)	0.031*** (0.003)	0.021*** (0.003)	0.035*** (0.003)	0.008*** (0.001)	0.012*** (0.002)	0.002 (0.002)
Private Rented	0.012*** (0.003)	0.013*** (0.003)	0.001 (0.003)	-0.000 (0.001)	-0.002 (0.001)	0.005 (0.003)	-0.002 (0.001)	0.014*** (0.003)	0.008* (0.004)	0.015*** (0.003)	0.002 (0.002)	0.006* (0.003)	-0.001 (0.002)
Constant	0.023* (0.011)	0.083*** (0.013)	0.010 (0.011)	0.013* (0.005)	0.014** (0.005)	0.046*** (0.014)	0.048*** (0.006)	0.042*** (0.012)	0.043** (0.014)	0.053*** (0.012)	0.008 (0.006)	-0.028* (0.011)	-0.008 (0.010)
Observations	220166	220166	220166	220166	220166	220166	220166	220166	220166	220166	220166	220166	220166
Outcome Mean	0.08	0.16	0.07	0.02	0.01	0.16	0.01	0.08	0.16	0.1	0.02	0.1	0.07

Note: Model is an LPM with standard errors clustered by 2011 Ward. Each column contains a linear regression coefficient and standard error from a single model, which shows the effect of a 5 $\mu\text{g}/\text{m}^3$ increase. Neighbourhood fixed effects (2011 Ward dummies) are included but their coefficients are not reported. The pollution variable represents the mean pollution exposure level between 2002 and 2010. Statistical significance level: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table SM4: Models 1-3 Logit, Odds Ratios

	(1) Unconditional	(2) (1) With Individual and Household Controls	(3) (2) with 2011 Neighbourhood FE
Poor General Health	2.06*** [1.72,2.46]	1.39*** [1.29,1.51]	1.36** [1.10,1.67]
LTAL Illness	1.58*** [1.35,1.84]	1.12** [1.04,1.21]	1.06 [0.90,1.26]
Other Condition	1.29*** [1.19,1.39]	1.13*** [1.06,1.21]	0.99 [0.82,1.19]
Blindness	1.57*** [1.37,1.79]	1.07 [0.96,1.19]	1.11 [0.79,1.57]
Communication Difficulties	1.32** [1.11,1.57]	0.95 [0.84,1.07]	1.22 [0.80,1.85]
Mobility Difficulties	1.56*** [1.38,1.76]	1.17*** [1.10,1.25]	1.23* [1.05,1.45]
Learning Difficulties	1.28* [1.03,1.59]	0.96 [0.82,1.12]	0.83 [0.55,1.26]
Mental Health	1.74*** [1.50,2.01]	1.20*** [1.12,1.29]	1.17 [0.98,1.41]
Long-Term Pain	1.46*** [1.30,1.63]	1.14*** [1.07,1.22]	1.13 [0.97,1.30]
Breathing Difficulties	1.78*** [1.59,1.99]	1.35*** [1.28,1.43]	1.21* [1.04,1.40]
Memory Loss	1.90*** [1.59,2.27]	1.15* [1.03,1.28]	1.00 [0.70,1.41]
Chronic Illness	1.45*** [1.35,1.56]	1.21*** [1.14,1.28]	1.22* [1.03,1.44]
Deafness	1.33*** [1.24,1.44]	1.17*** [1.09,1.24]	1.24* [1.01,1.51]
Observations	209957	209957	209957
Controls	No	Yes	Yes
2011 Neighbourhood FE	No	No	Yes

Note: Each model is a logit model with standard errors clustered by 2011 Ward. Each cell contains an odds ratio (showing the effect of a 5 µg/m³ increase) and 95% confidence interval from a single model. The pollution variable represents the mean pollution exposure level between 2002 and 2010. Control variables (all measured in 2001): Age group, gender, country of birth, economic status, highest education level, religion, marital status; household family type, household no. of dependent children, household no. of cars, household tenure, and activity-limiting disability and general health in 2001. Neighbourhood fixed effects (Ward dummies) are for residential neighbourhood in 2011 (Model 3). The logit estimation sample differs from the LPM sample because some 2011 Wards perfectly predict outcomes (e.g. some Wards have no residents with a given health outcome) and therefore maximum likelihood estimates for these coefficients are infinite. Consequently, 10,209 individuals were excluded if they lived in any affected 2011 Ward. LPM estimates from this slightly reduced sample are qualitatively identical to the logit estimates presented here. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table SM5: Models 1-3 Logit, Average Marginal Effects

	(1) Unconditional	(2) (1) With Individual and Household Controls	(3) (2) with 2011 Neighbourhood FE
Poor General Health	0.0543*** [0.0396,0.0690]	0.0201*** [0.0152,0.0250]	0.0182** [0.0058,0.0307]
LTAL Illness	0.0620*** [0.0399,0.0842]	0.0106** [0.0035,0.0177]	0.0058 [-0.0097,0.0212]
Other Condition	0.0164*** [0.0112,0.0215]	0.0078*** [0.0036,0.0120]	-0.0007 [-0.0125,0.0111]
Blindness	0.0086*** [0.0060,0.0113]	0.0013 [-0.0007,0.0033]	0.0020 [-0.0043,0.0082]
Communication Difficulties	0.0037** [0.0013,0.0061]	-0.0007 [-0.0023,0.0009]	0.0025 [-0.0029,0.0079]
Mobility Difficulties	0.0613*** [0.0438,0.0787]	0.0160*** [0.0093,0.0228]	0.0210* [0.0049,0.0371]
Learning Difficulties	0.0031* [0.0003,0.0058]	-0.0005 [-0.0023,0.0012]	-0.0020 [-0.0066,0.0025]
Mental Health	0.0412*** [0.0297,0.0528]	0.0124*** [0.0078,0.0169]	0.0107 [-0.0014,0.0227]
Long-Term Pain	0.0499*** [0.0346,0.0653]	0.0141*** [0.0070,0.0212]	0.0128 [-0.0029,0.0285]
Breathing Difficulties	0.0540*** [0.0428,0.0652]	0.0260*** [0.0210,0.0309]	0.0160* [0.0031,0.0289]
Memory Loss	0.0142*** [0.0100,0.0184]	0.0029* [0.0006,0.0053]	-0.0001 [-0.0074,0.0072]
Chronic Illness	0.0332*** [0.0269,0.0396]	0.0149*** [0.0104,0.0193]	0.0155* [0.0022,0.0288]
Deafness	0.0193*** [0.0143,0.0243]	0.0093*** [0.0053,0.0133]	0.0129* [0.0008,0.0250]
Observations	209957	209957	209957
Controls	No	Yes	Yes
2011 Neighbourhood FE	No	No	Yes

Note: Each model is a logit model with standard errors clustered by 2011 Ward. Each cell contains an average marginal effect (showing the effect of a 5 $\mu\text{g}/\text{m}^3$ increase) and 95% confidence interval from a single model. The pollution variable represents the mean pollution exposure level between 2002 and 2010. Control variables (all measured in 2001): Age group, gender, country of birth, economic status, highest education level, religion, marital status; household family type, household no. of dependent children, household no. of cars, household tenure, and activity-limiting disability and general health in 2001. Neighbourhood fixed effects (Ward dummies) are for residential neighbourhood in 2011 (Model 3). The logit estimation sample differs from the LPM sample because some 2011 Wards perfectly predict outcomes (some Wards have no residents with a given health outcome) and therefore maximum likelihood estimates for these coefficients are infinite. Consequently, 10,209 individuals were excluded if they lived in any affected 2011 Ward. LPM estimates from this reduced sample are qualitatively identical to the logit estimates presented here. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table SM6: Effects of NO₂ and SO₂ Exposure on Self-Reported Health, Model 3

	Nitrogen Dioxide	Sulphur Dioxide
Poor General Health	0.0057*** [0.0025,0.0089]	0.0093*** [0.0041,0.0145]
LTAL Illness	0.0028 [-0.0012,0.0068]	0.0061* [0.0002,0.0120]
Other Condition	0.0000 [-0.0032,0.0033]	0.0010 [-0.0040,0.0059]
Blindness	0.0004 [-0.0012,0.0020]	0.0018 [-0.0007,0.0044]
Communication Difficulties	0.0005 [-0.0011,0.0020]	0.0005 [-0.0017,0.0027]
Mobility Difficulties	0.0061** [0.0022,0.0101]	0.0134*** [0.0072,0.0195]
Learning Difficulties	-0.0020* [-0.0035,-0.0004]	-0.0026* [-0.0046,-0.0005]
Mental Health	0.0030 [-0.0006,0.0065]	0.0017 [-0.0031,0.0065]
Long-Term Pain	0.0049* [0.0007,0.0090]	0.0041 [-0.0021,0.0103]
Breathing Difficulties	0.0031 [-0.0004,0.0066]	0.0109*** [0.0054,0.0164]
Memory Loss	0.0010 [-0.0010,0.0029]	0.0004 [-0.0025,0.0033]
Chronic Illness	0.0048** [0.0015,0.0081]	0.0067** [0.0017,0.0117]
Deafness	0.0032* [0.0002,0.0063]	0.0045 [-0.0001,0.0092]
Observations	220166	220166
Controls	Yes	Yes
2011 Neighbourhood FE	Yes	Yes

Note: Each model is an LPM with standard errors clustered by 2011 Ward. Each cell contains a linear regression coefficient (showing the effect of a 5 µg/m³ increase) and 95% confidence intervals from a single model. The pollution variable represents the pollution exposure level averaged over the 2002-2010 period. Control variables: Age group, gender, country of birth, economic status, highest education level, religion, marital status; household family type, household no. of dependent children, household no. of cars, household tenure, and activity-limiting disability and general health in 2001. Neighbourhood fixed effects (Ward dummies) are for residential neighbourhood in 2011 (Model 3). Means (standard deviations) for NO₂ and SO₂ exposure are 10.74 (5.23) and 3.79 (2.61) µg/m³ respectively. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table SM7: Effects of PM_{2.5} Exposure on Health by 2001 Age Group

	Poor Gen. Health	LTAL Illness	Other Condition	Blindness	Communication	Mobility Diff.	Learning Diff.	Mental Health	Long-Term Pain	Breathing Diff.	Memory Loss	Chronic Illness	Deafness
16-19	-0.010 (0.007)	-0.014 (0.009)	-0.000 (0.007)	-0.002 (0.003)	0.004 (0.004)	-0.005 (0.008)	0.002 (0.005)	0.007 (0.009)	-0.010 (0.008)	-0.015 (0.010)	-0.004 (0.004)	0.013* (0.006)	0.008 (0.006)
20-29	-0.006 (0.007)	-0.012 (0.008)	-0.006 (0.006)	-0.001 (0.003)	-0.003 (0.003)	0.002 (0.008)	-0.010** (0.003)	0.003 (0.007)	0.001 (0.008)	-0.004 (0.007)	-0.002 (0.004)	0.006 (0.006)	0.010 (0.005)
30-39	0.018* (0.007)	0.015 (0.008)	0.005 (0.006)	0.003 (0.003)	0.002 (0.003)	0.018* (0.008)	-0.006* (0.003)	0.030*** (0.007)	0.017* (0.008)	0.004 (0.007)	0.004 (0.004)	0.012* (0.006)	0.007 (0.005)
40-49	0.042*** (0.007)	0.021* (0.008)	0.003 (0.006)	-0.001 (0.003)	0.001 (0.003)	0.036*** (0.009)	-0.005 (0.003)	0.028*** (0.008)	0.028*** (0.008)	0.026*** (0.007)	0.006 (0.004)	0.023** (0.007)	0.012 (0.006)
50-59	0.038*** (0.009)	0.026* (0.010)	0.004 (0.007)	0.002 (0.004)	-0.001 (0.003)	0.056*** (0.010)	-0.009** (0.003)	-0.004 (0.009)	0.026* (0.010)	0.045*** (0.009)	-0.002 (0.004)	0.032*** (0.009)	0.029*** (0.007)
60-69	0.029** (0.010)	0.010 (0.012)	-0.000 (0.009)	0.017** (0.006)	-0.000 (0.004)	0.034** (0.012)	-0.006 (0.003)	-0.023** (0.008)	0.008 (0.011)	0.050*** (0.011)	0.005 (0.006)	0.028** (0.010)	0.032** (0.010)
70-75	0.040** (0.014)	-0.008 (0.018)	0.016 (0.013)	0.017 (0.012)	0.001 (0.008)	-0.005 (0.019)	-0.000 (0.005)	-0.022 (0.012)	0.035 (0.018)	0.023 (0.016)	0.028* (0.013)	0.016 (0.016)	-0.001 (0.018)
Observations	220166	220166	220166	220166	220166	220166	220166	220166	220166	220166	220166	220166	220166

Note: Table contains linear regression coefficients showing the effect of a 5 $\mu\text{g}/\text{m}^3$ increase in PM_{2.5} exposure by age group. Each column reports a single model containing the PM_{2.5} exposure variable, control variables (including 2011 neighbourhood fixed effect) and PM_{2.5} interacted with 2001 age group. The pollution variable represents the mean pollution exposure level between 2002 and 2010. Statistical significance level: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table SM8: Effects of PM_{2.5} Exposure on Health by Gender

	Poor Gen. Health	LTAL Illness	Other Condition	Blindness	Communication	Mobility Diff.	Learning Diff.	Mental Health	Long-Term Pain	Breathing Diff.	Memory Loss	Chronic Illness	Deafness
PM _{2.5}													
Female	0.023*** (0.006)	0.010 (0.007)	0.001 (0.006)	0.001 (0.003)	-0.001 (0.003)	0.027*** (0.007)	-0.009** (0.003)	0.013* (0.006)	0.028*** (0.007)	0.028*** (0.007)	0.000 (0.003)	0.015* (0.006)	0.016** (0.005)
Male	0.018** (0.006)	0.007 (0.007)	0.002 (0.006)	0.005 (0.003)	0.001 (0.003)	0.020* (0.008)	-0.003 (0.003)	0.005 (0.007)	0.000 (0.008)	0.005 (0.007)	0.005 (0.004)	0.022*** (0.006)	0.013* (0.006)
Observations	220166	220166	220166	220166	220166	220166	220166	220166	220166	220166	220166	220166	220166

Note: Table contains linear regression coefficients showing the effect of a 5 µg/m³ increase in PM_{2.5} exposure by gender. Each column reports a single model in which PM_{2.5} is interacted with gender. The pollution variable represents the mean pollution exposure level between 2002 and 2010. Statistical significance level: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table SM9: Effects of PM_{2.5} Exposure on Health by 2001 General Health

	Poor Gen. Health	LTAL Illness	Other Condition	Blindness	Communication	Mobility Diff.	Learning Diff.	Mental Health	Long-Term Pain	Breathing Diff.	Memory Loss	Chronic Illness	Deafness
Good Health	0.008 (0.006)	0.003 (0.007)	0.001 (0.005)	0.001 (0.003)	-0.000 (0.003)	0.014* (0.007)	-0.007** (0.003)	0.006 (0.006)	0.012 (0.007)	0.005 (0.006)	-0.000 (0.003)	0.015** (0.006)	0.012* (0.005)
Fairly Good Health	0.030*** (0.007)	0.015 (0.009)	0.005 (0.007)	0.003 (0.004)	0.001 (0.003)	0.038*** (0.010)	-0.005 (0.003)	0.015* (0.007)	0.023* (0.010)	0.031*** (0.008)	0.002 (0.004)	0.018* (0.008)	0.015* (0.007)
Not Good Health	0.074*** (0.012)	0.027* (0.011)	-0.003 (0.009)	0.011* (0.005)	0.002 (0.005)	0.052*** (0.012)	-0.003 (0.004)	0.017 (0.010)	0.014 (0.013)	0.064*** (0.012)	0.018** (0.007)	0.038*** (0.011)	0.027** (0.009)
Observations	220166	220166	220166	220166	220166	220166	220166	220166	220166	220166	220166	220166	220166

Note: Table contains linear regression coefficients showing the effect of a 5 µg/m³ increase in PM_{2.5} exposure by general health in 2001. Each column reports a single model containing the PM_{2.5} exposure variable, control variables (including 2011 neighbourhood fixed effect) and PM_{2.5} interacted with general health. The pollution variable represents the mean pollution exposure level between 2002 and 2010. Statistical significance level: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table SM10: Effects of PM_{2.5} Exposure on Health by 2001 Long-Term Limiting Illness

	Poor Gen. Health	LTAL Illness	Other Condition	Blindness	Communication	Mobility Diff.	Learning Diff.	Mental Health	Long-Term Pain	Breathing Diff.	Memory Loss	Chronic Illness	Deafness
No Long-Term Illness	0.010 (0.006)	0.004 (0.007)	0.001 (0.005)	0.001 (0.003)	0.001 (0.003)	0.016* (0.007)	-0.006* (0.003)	0.010 (0.006)	0.013 (0.007)	0.008 (0.006)	-0.000 (0.003)	0.014* (0.006)	0.013* (0.005)
Has Long-Term Illness	0.064*** (0.009)	0.028** (0.010)	0.003 (0.007)	0.010* (0.004)	-0.003 (0.004)	0.054*** (0.010)	-0.007 (0.004)	0.006 (0.008)	0.024* (0.011)	0.055*** (0.010)	0.012* (0.005)	0.035*** (0.009)	0.022** (0.007)
Observations	220166	220166	220166	220166	220166	220166	220166	220166	220166	220166	220166	220166	220166

Note: Table contains linear regression coefficients showing the effect of a 5 µg/m³ increase in PM_{2.5} exposure by presence of a long-term activity-limiting illness (LTAL) in 2001. Each column reports a single model containing the PM_{2.5} exposure variable, control variables (including 2011 neighbourhood fixed effect) and PM_{2.5} interacted with LTAL. The pollution variable represents the mean pollution exposure level between 2002 and 2010. Statistical significance level: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table SM11: Effects of PM_{2.5} Exposure on Health by 2001 Household Tenure

	Poor Gen. Health	LTAL Illness	Other Condition	Blindness	Communication Diff.	Mobility Diff.	Learning Diff.	Mental Health	Long-Term Pain	Breathing Diff.	Memory Loss	Chronic Illness	Deafness
Owner Occupied	0.020*** (0.006)	0.008 (0.007)	0.001 (0.006)	0.003 (0.003)	0.000 (0.003)	0.023** (0.007)	-0.006* (0.003)	0.008 (0.006)	0.016* (0.007)	0.017** (0.006)	0.002 (0.003)	0.018** (0.006)	0.014** (0.005)
Social Rented	0.025** (0.009)	0.009 (0.011)	0.003 (0.007)	0.003 (0.004)	0.001 (0.004)	0.023* (0.010)	-0.001 (0.004)	0.012 (0.008)	0.008 (0.010)	0.020* (0.009)	0.007 (0.005)	0.021** (0.008)	0.019** (0.007)
Private Rented	0.015 (0.010)	0.016 (0.011)	0.002 (0.009)	0.002 (0.005)	-0.001 (0.005)	0.029** (0.011)	-0.016*** (0.004)	0.019 (0.011)	0.017 (0.012)	0.014 (0.011)	-0.006 (0.006)	0.014 (0.009)	0.013 (0.009)
Observations	220166	220166	220166	220166	220166	220166	220166	220166	220166	220166	220166	220166	220166

Note: Table contains linear regression coefficients showing the effect of a 5 µg/m³ increase in PM_{2.5} exposure by household tenure type in 2001. Each column reports a single model containing the PM_{2.5} exposure variable, control variables (including 2011 neighbourhood fixed effect) and PM_{2.5} interacted with household tenure. The pollution variable represents the mean pollution exposure level between 2002 and 2010. Statistical significance level: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Figure SM1: Northern Ireland Electoral Ward and 1km² Grid Square Geographies

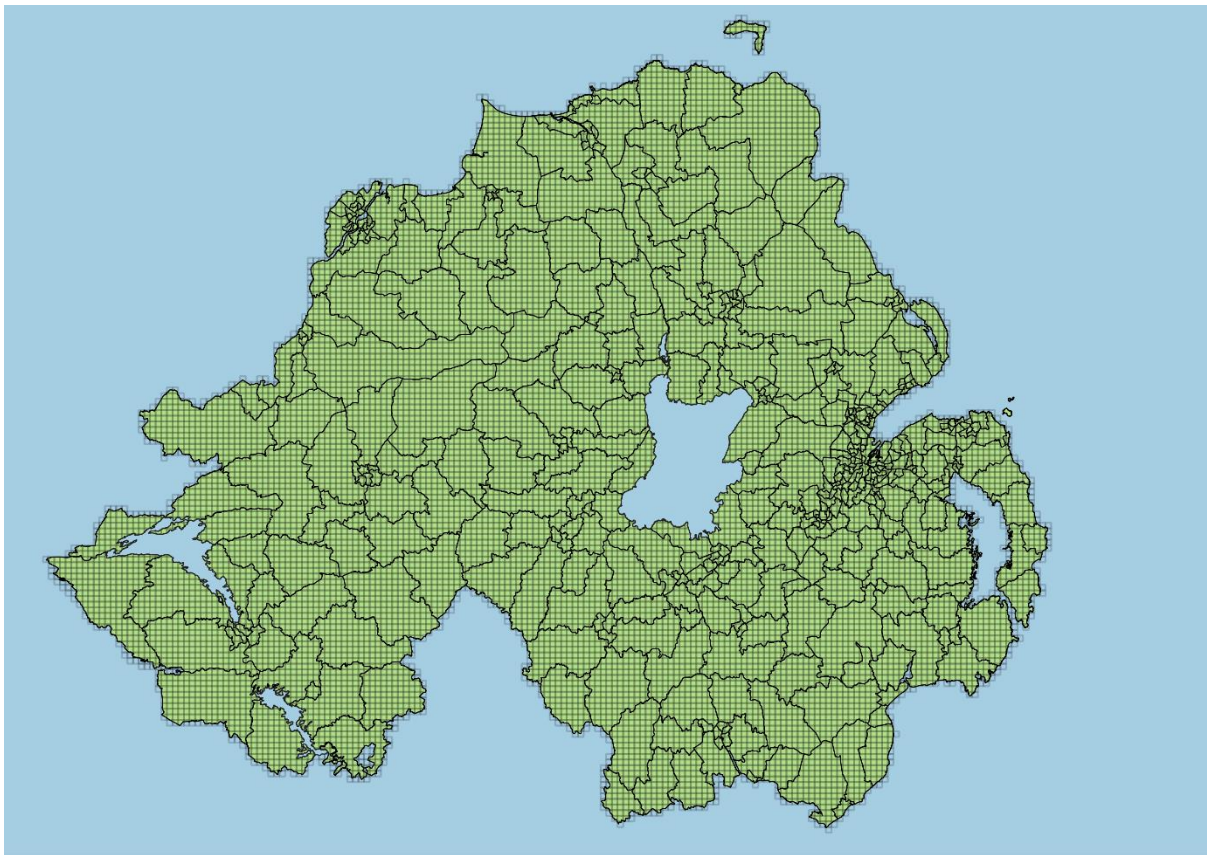
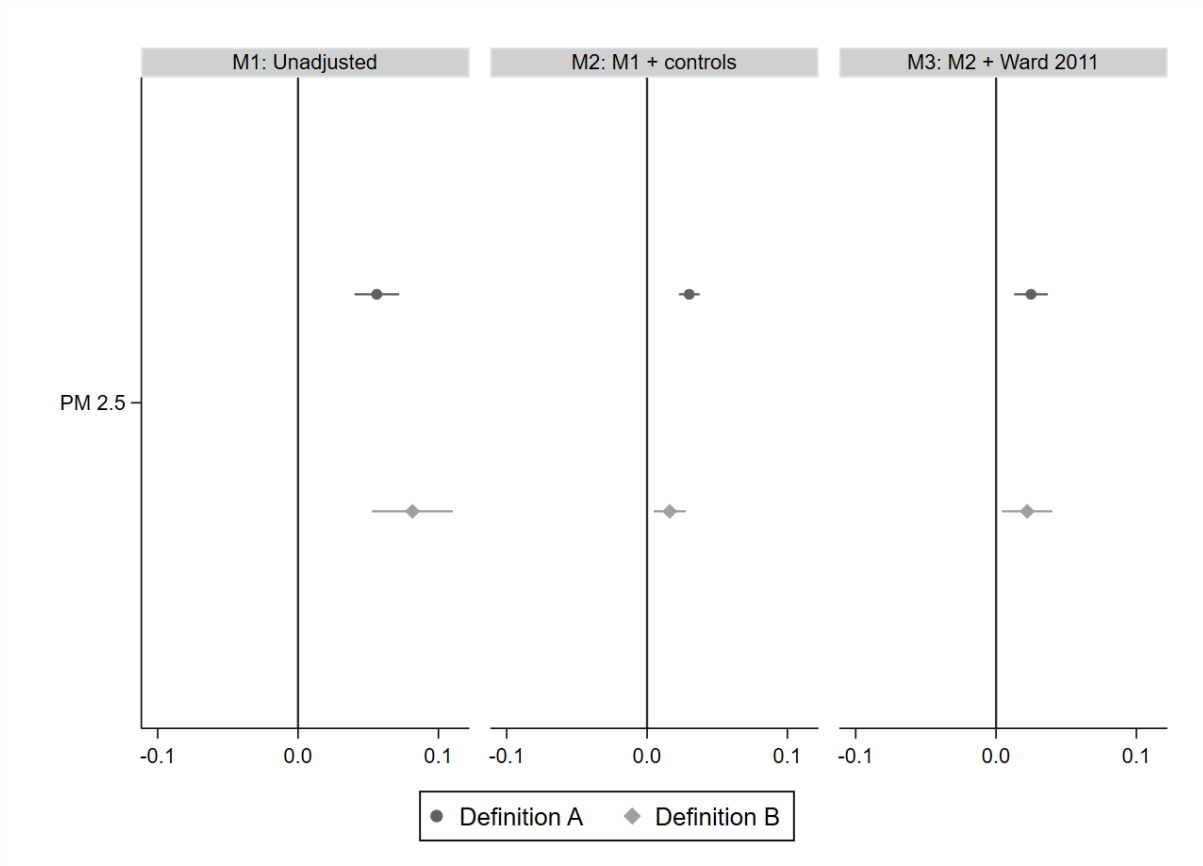
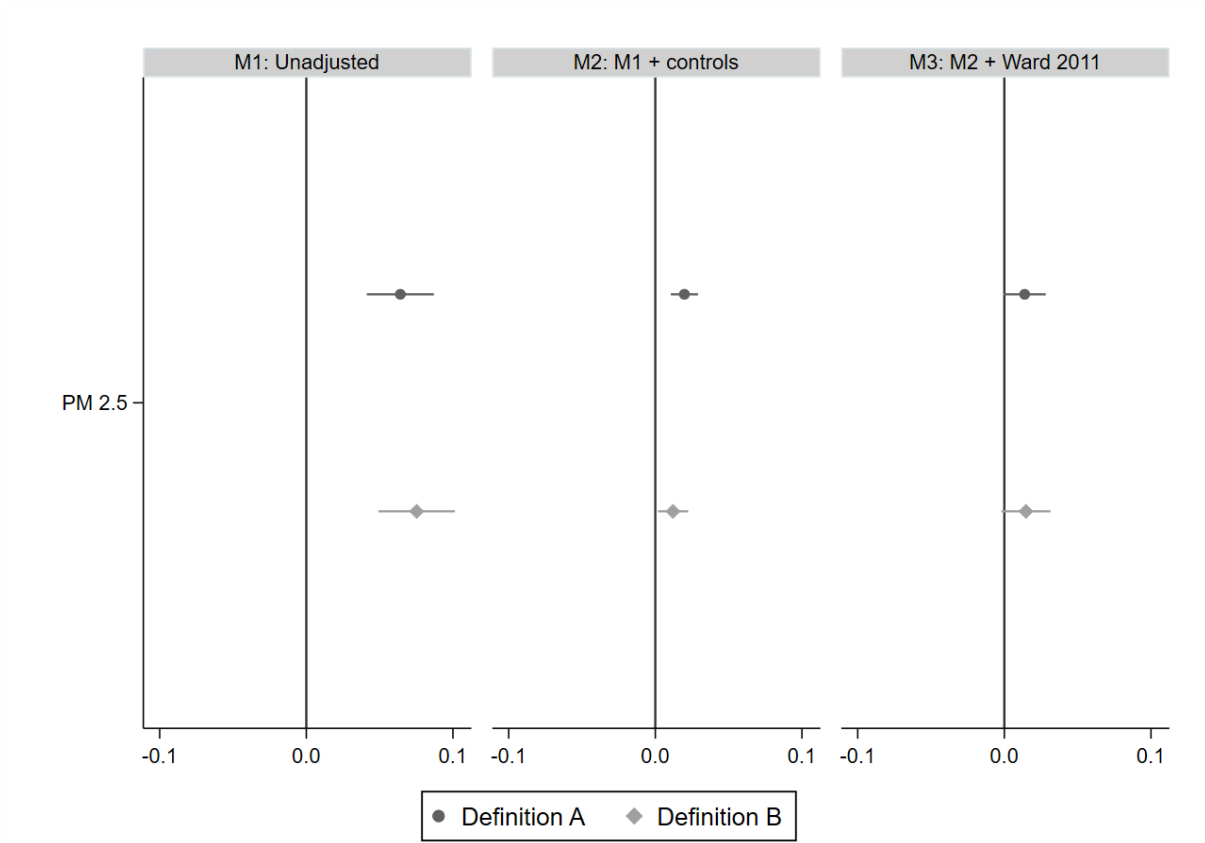


Figure SM2: Effects of PM_{2.5} Exposure on the Probability of Poor General Health in 2011, by Health Definition



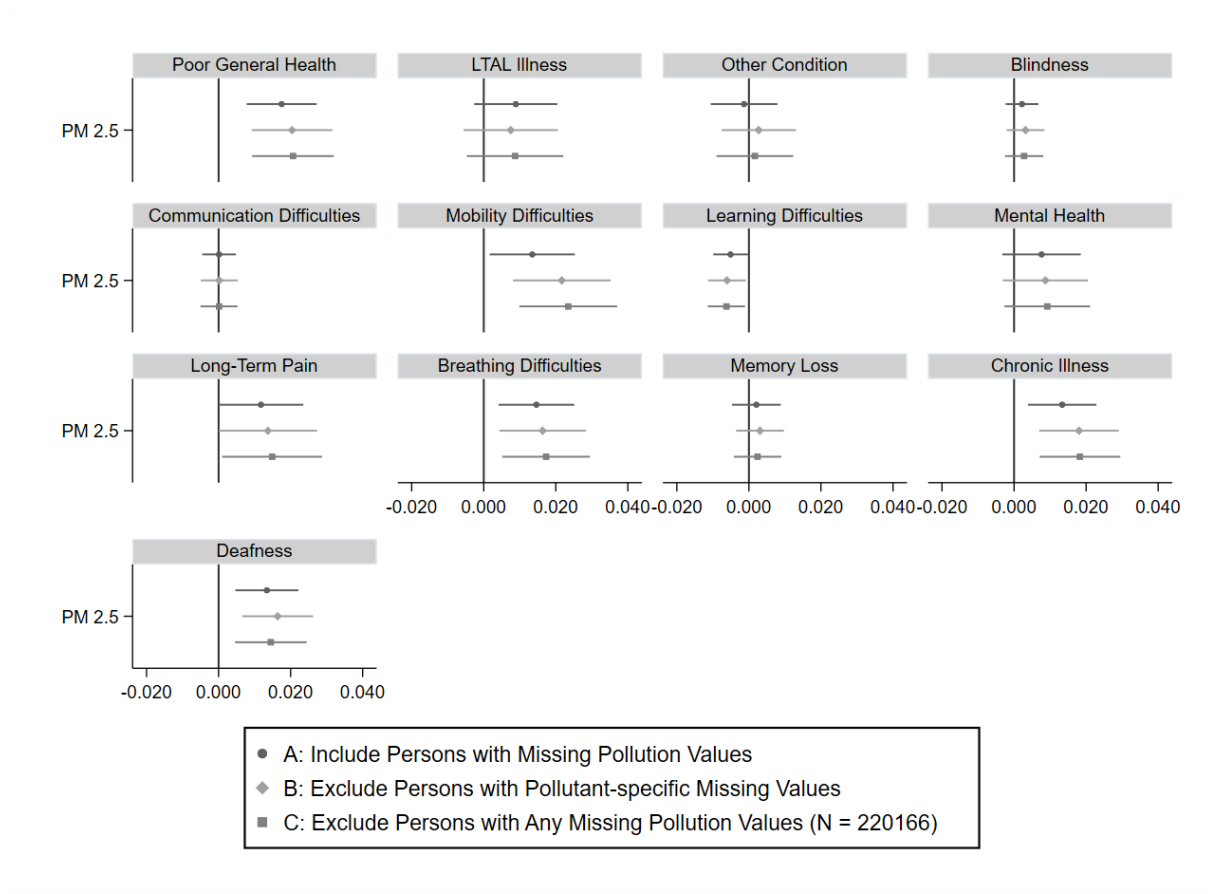
Notes: Plot displays linear regression coefficients and 95% confidence intervals, showing the effects of a 5 $\mu\text{g}/\text{m}^3$ unit increase in exposure. Definition A (used in the main analysis) classifies individuals as having poor general health (coded 1) if they report ‘very bad’ or ‘bad’ general health, while those reporting ‘fair’, ‘good’, or ‘very good’ are coded 0. In Definition B, those reporting ‘fair’ general health are also coded 1.

Figure SM3: Effects of PM_{2.5} Exposure on the Probability of a Long-Term Activity-Limiting Illness or Disability in 2011, by Definition



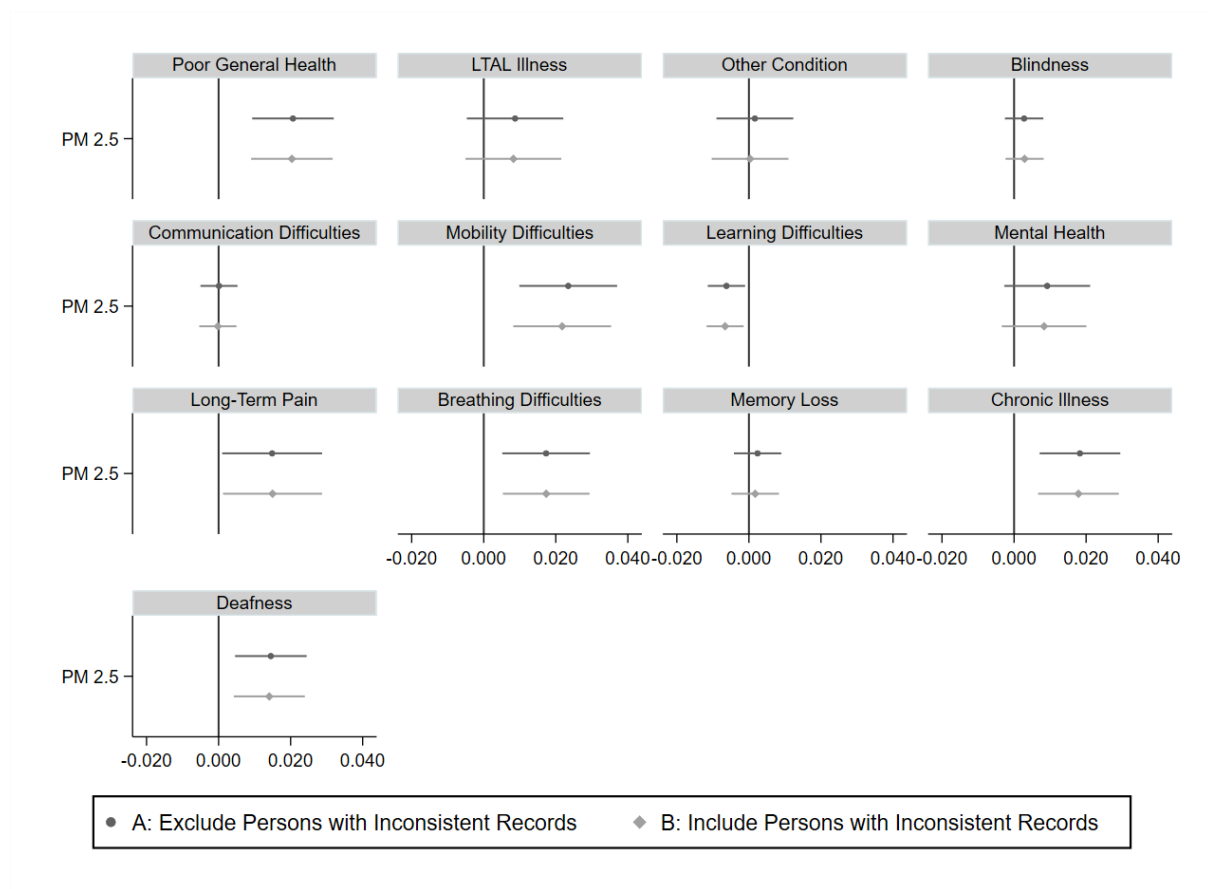
Notes: Plot displays linear regression coefficients and 95% confidence intervals, showing the effects of a 5 $\mu\text{g}/\text{m}^3$ unit increase in exposure. Definition A (used in the main analysis) classifies individuals as having a long-term activity-limiting illness (coded 1) if they report that their day-to-day activities are ‘limited a lot’ by a health problem or disability which has lasted, or is expected to last, at 12 months, while those reporting ‘limited a little’ or ‘no’ (having no activity-limiting illness) are coded 0. In Definition B, those reporting ‘limited a little’ are also coded 1. All estimates are based on model 3 which includes 2011 neighbourhood fixed effects.

Figure SM4: Adjusted Effect of PM_{2.5} Exposure on Self-Reported Health in 2011, by Sample



Notes: Plot shows linear regression coefficients and 95% confidence intervals, showing the effects of a 5 $\mu\text{g}/\text{m}^3$ unit increase in exposure. Sample C (the main sample) excludes anyone with one or more missing pollution values, so that long-term exposure is calculated for individuals with a complete pollution history between 2001 and 2010. Sample A includes individuals with missing pollution values in one or more time periods (but enough data to calculate a long-term exposure value). Sample B excludes individuals with missing values specific to a particular pollutant, e.g., anyone with one or more missing NO_2 values are excluded from the NO_2 model but included in the $\text{PM}_{2.5}$ model if they have complete $\text{PM}_{2.5}$ data. Sample size varies by pollutant in Sample A and Sample B, but is fixed in Sample C. All estimates are based on model 3 which includes 2011 neighbourhood fixed effects.

Figure SM5: Adjusted Effect of PM_{2.5} Exposure on Self-Reported Health, by Sample Inclusion



Notes: Plot shows linear regression coefficients and 95% confidence intervals, showing the effects of a 5 µg/m³ unit increase in exposure. All estimates come from separate models, where the main model excludes individuals with at least one type of inconsistent record, e.g., no pollution table match. All estimates are based on model 3 which includes 2011 neighbourhood fixed effects.