

Supplementary material: Long-term exposure to air-pollution and COVID-19 mortality in England: a hierarchical spatial analysis

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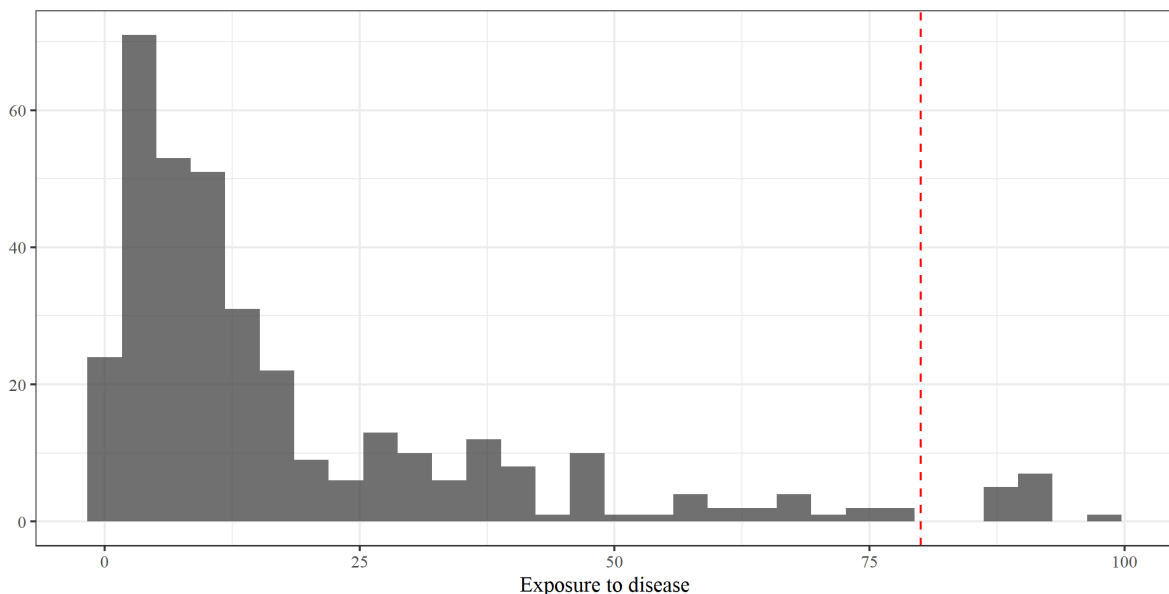
S1 Text

S1.1 Confounders

High risk occupation In the main analysis, we accounted for high risk occupational exposure by including a covariate for the proportions of workers highly exposed to the infection. We considered estimates of disease proximity released by ONS as a measure of risk of each job categories. This score varies on a scale from 0–100, where 75 corresponds to being exposed to the infection “Once a week or more but not every day”. Based on the distribution of this score (see histogram below), we selected as *high risk occupations* those with a score of 80 or higher (see Table S1 for a complete list). We then used occupation estimates from the 2011 census and calculated the proportion of workers in these *high risk occupations*.

Smoking, obesity and pre-existing conditions Estimated prevalence for smoking and obesity, as well as the the pre-existing conditions included in the post-hoc analysis (chronic obstructive pulmonary disease, hypertension and diabetes mellitus) are retrieved from the Quality and Outcomes Framework of Public Health England. Estimates are available for each fiscal year since 2013/2014. We selected as a time reference 2018/2019, which was the most recent at the time of the analysis. As data refer to General Practitioner (GP) catchment areas, we projected the estimated prevalence on LSOAs. Thus for the prevalence of the i -th LSOA, we computed the mean of the prevalences of the GP catchment areas that contain the centroid of the i -th LSOA. While GP catchment areas are fewer than LSOAs, there is a great deal of overlap between practices, which allows the projected values to account for some of the missing spatial variation. We imputed missing values with the mean of the first order neighbors.

Exposure to disease estimate for occupational categories



S1.2 Epidemiological models

We model COVID–19 death counts Y_l in each LSOA $l = 1, \dots, N$, where N is the total number of LSOAs in England, as a Poisson random variable

$$Y_l \sim \text{Poisson}(E_l \theta_l) \quad l = 1, \dots, N$$

where E_l is the expected number of deaths in LSOA l adjusted for age, sex and ethnicity by means of indirect standardization, and θ_l is the standardised mortality ratio (SMR).

We consider the following four log-linear models:

Model 1: Unadjusted

$$\log(\theta_l) = \beta_0 + \beta \tilde{X}_l \quad l = 1, \dots, N$$

Model 2: Adjusted for spatial autocorrelation

$$\log(\theta_l) = \beta_0 + \beta \tilde{X}_l + b_l \quad l = 1, \dots, N$$

Model 3: Adjusted for confounding

$$\log(\theta_l) = \beta_0 + \beta \tilde{X}_l + \sum_r \gamma_r Z_{rl} \quad l = 1, \dots, N \text{ and } r = 1, \dots, R$$

Model 4: Adjusted for confounding and spatial autocorrelation

$$\log(\theta_l) = \beta_0 + \beta \tilde{X}_l + \sum_r \gamma_r Z_{rl} + b_l \quad l = 1, \dots, N \text{ and } r = 1, \dots, R$$

where β_0 is an intercept term standing for the mean SMR over the spatial domain, β is the log-increase of COVID-19 death rate for $1 \mu\text{g}/\text{m}^3$ in the pollutant, \tilde{X}_l denotes the population weighted version of each pollutant at the l -th LSOA, Z_l represents the r -th confounder at the l -th LSOA as defined in Table 1 (Main Manuscript), γ_r the corresponding effects of the r -th confounder and b_l is the random effect which accounts for the spatial autocorrelation. We adopt the formulation of [1, 2] and we define

$$b_l = \frac{1}{\tau} \left(\sqrt{1 - \varphi} v_l + \sqrt{\varphi} u_l \right)$$

where u_l is a spatially structured random effect, v_l is an i.i.d. random effect [3]. Both u_l and v_l are normalized to have variance 1, so that τ is the marginal precision and the mixing parameter φ represent the proportion of marginal variance explained by the spatial component u_l .

We specify non informative Normal(0, 100) prior distributions for β_0, β and $\boldsymbol{\gamma}$, and PC priors for τ and φ [1]. In particular, we set the PC priors for τ so that $\Pr(\tau > 1) = 0.01$, implying that is unlikely to have a spatial relative risk higher than $\exp(2)$ based solely on unknown spatial confounding. For φ we set $\Pr(\varphi < 0.5) = 0.5$ reflecting our lack of knowledge about which spatial component, the unstructured or structured, should dominate the field.

Tables

Table S1: Occupations with high risk exposure to COVID–19 patients (Text S1.1).

UK SOC 2010 Code	Occupation title
2211	Medical practitioners
2215	Dental practitioners
2216	Veterinarians
2217	Medical radiographers
2231	Nurses
2232	Midwives
3213	Paramedics
3218	Medical and dental technicians
6141	Nursing auxiliaries and assistants
6142	Ambulance staff (excluding paramedics)
6143	Dental nurses
6144	Houseparents and residential wardens
6147	Care escorts

Abbreviations: SOC, Standard Occupational Classification.

Table S2: Relative frequencies of **age and sex** across COVID-19 deaths up to 30-06-2020 and 23-03-2020 in England.

Age Class	Deaths Until 30-06-2020			Deaths Until 23-03-2020		
	Females	Males	Total Cumulative	Female	Males	Total Cumulative
<1	0.000	0.000	0.000	0.000	0.000	0.000
1-4	0.000	0.000	0.000	0.000	0.000	0.000
5-9	0.000	0.000	0.000	0.000	0.000	0.000
10-14	0.000	0.000	0.000	0.000	0.000	0.000
15-19	0.000	0.000	0.001	0.000	0.002	0.001
20-24	0.001	0.000	0.001	0.003	0.000	0.003
25-29	0.001	0.001	0.002	0.003	0.002	0.006
30-34	0.002	0.002	0.004	0.003	0.005	0.010
35-39	0.003	0.003	0.007	0.003	0.000	0.011
40-44	0.004	0.006	0.012	0.007	0.010	0.020
45-49	0.008	0.011	0.022	0.010	0.010	0.030
50-54	0.015	0.020	0.040	0.017	0.024	0.052
55-59	0.023	0.036	0.071	0.038	0.046	0.095
60-64	0.035	0.052	0.116	0.049	0.046	0.142
65-69	0.049	0.069	0.176	0.066	0.073	0.212
70-74	0.079	0.112	0.274	0.101	0.117	0.322
75-79	0.121	0.151	0.412	0.101	0.141	0.447
80-84	0.183	0.198	0.604	0.184	0.178	0.628
85-89	0.215	0.189	0.804	0.212	0.217	0.842
90+	0.259	0.147	1.000	0.201	0.127	1.000

Table S3: Relative frequency of the **ethnicity** across COVID-19 deaths up to 30-06-2020 and 23-03-2020 in England.

Ethnicity	Deaths up to 30-06-202	Deaths up to 23-03-2020
Asian British	0.060	0.115
Black British	0.042	0.105
Mixed Ethnic Group	0.006	0.010
Other Ethnic Group	0.018	0.039
White British	0.874	0.732

Table S4: **Main results** for long-term (2014–2018) averaged NO₂ exposure on COVID–19 mortality up to **June 30, 2020** at the **lower layer super output area level**.

	Model 1		Model 2		Model 3		Model 4	
	Median	95% CrI	Median	95% CrI	Median	95% CrI	Median	95% CrI
Intercept	0.663	(0.646, 0.681)	0.76	(0.701, 0.823)	0.689	(0.641, 0.739)	0.848	(0.750, 0.956)
NO ₂ ¹	1.026	(1.024, 1.027)	1.013	(1.008, 1.018)	1.018	(1.015, 1.021)	1.005	(0.998, 1.012)
IMD2 ²	-	-	-	-	1.023	(0.976, 1.074)	1.011	(0.962, 1.063)
IMD3 ²	-	-	-	-	1.012	(0.965, 1.063)	1.014	(0.964, 1.069)
IMD4 ²	-	-	-	-	1.029	(0.977, 1.081)	1.017	(0.962, 1.074)
IMD5 ²	-	-	-	-	1.038	(0.987, 1.093)	1.014	(0.959, 1.074)
Days Difference ³	-	-	-	-	0.998	(0.986, 1.009)	1.007	(0.988, 1.026)
Number of Cases ⁴	-	-	-	-	1.095	(1.082, 1.109)	1.097	(1.072, 1.124)
Total ICU Beds ⁵	-	-	-	-	0.933	(0.921, 0.944)	0.982	(0.963, 1.001)
Temperature ⁶	-	-	-	-	0.902	(0.887, 0.918)	0.948	(0.904, 0.994)
Relative Humidity ⁷	-	-	-	-	0.864	(0.850, 0.879)	0.927	(0.882, 0.972)
log Population ⁸	-	-	-	-	0.966	(0.952, 0.979)	0.989	(0.974, 1.004)
Urban ⁹	-	-	-	-	1.076	(1.032, 1.125)	1.008	(0.960, 1.061)
High risk occupation ¹⁰	-	-	-	-	0.995	(0.981, 1.009)	0.999	(0.982, 1.017)
Smoking ¹¹	-	-	-	-	1.026	(1.009, 1.044)	1.036	(1.010, 1.064)
Obesity ¹²	-	-	-	-	1.025	(1.009, 1.041)	1.011	(0.985, 1.036)
τ ¹³	-	-	8.127	(7.067, 9.384)	-	-	9.005	(7.758, 10.499)
ϕ ¹⁴	-	-	0.990	(0.945, 0.999)	-	-	0.989	(0.937, 0.998)

Abbreviations: CrI, Credibility intervals; IMD, Index of Multiple Deprivation; ICU, Intensive Care Unit

¹ Population weighted modelled exposure to NO₂ as an average of 2014–2018 per 1km grid. The interpretation of the effect is for an increase of 1 $\mu\text{g}/\text{m}^3$ in the exposure.

² Quintiles of index of Multiple Deprivation without the air-quality domain by lower layer super output area as of 2019. The baseline category is the first, indicating most deprived areas, whereas the fifth category indicated the least deprived.

³ Days difference since first reported case per lower tier local authority, up to June 30, 2020. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the days i.e. 8.36 days.

⁴ Number of tested positive COVID–19 cases per lower tier local authority up to June 30, 2020. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the tested positive cases i.e. 957 cases.

⁵ Number of total ICU beds per population per NHS trust as of February 2020. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the number of beds per population i.e. 0.03 beds per population.

⁶ Modelled exposure to long-term (2014–2018) averaged temperature in 1km grid resolution. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the temperature i.e. 0.78 °C.

⁷ Modelled exposure to long-term (2014–2018) average of hourly relative humidity over the year (%) in 1km grid resolution. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the relative humidity i.e. 2.34%.

⁸ Logged population estimates in 2018 by lower layer super output area. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the log population i.e. 0.21 log people.

⁸ Degrees of urbanicity as of 2011 by lower layer super output area. The baseline category is rural areas.

¹⁰ Proportion of workers (as of 2011) in high risk occupation by middle layer super output areas with exposure more than once per week with an infected person. The covariate was scaled and thus the interpretation of the effect is per standard

deviation of the proportion i.e. 1.5%.

¹¹ Smoking prevalence by general practitioner area in 2018–2019. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the prevalence i.e. 4.2.

¹² Obesity prevalence by general practitioner area in 2018–2019. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the prevalence i.e. 2.8.

¹³ The precision parameter of the spatial field as defined in Text S1.2.

¹⁴ The mixing parameter of the spatial field as defined in Text S1.2.

Table S5: **Main results** for long-term (2014–2018) averaged $PM_{2.5}$ exposure on COVID–19 mortality up to June 30, 2020 at the **lower layer super output area level**.

	Model 1		Model 2		Model 3		Model 4	
	Median	95% CrI	Median	95% CrI	Median	95% CrI	Median	95% CrI
Intercept	0.655	(0.613, 0.699)	0.556	(0.422, 0.732)	0.563	(0.495, 0.640)	0.801	(0.561, 1.141)
$PM_{2.5}^1$	1.044	(1.037, 1.051)	1.054	(1.025, 1.084)	1.049	(1.037, 1.062)	1.014	(0.979, 1.051)
IMD2 ²	-	-	-	-	1.019	(0.971, 1.069)	1.011	(0.962, 1.063)
IMD3 ²	-	-	-	-	0.998	(0.952, 1.048)	1.014	(0.963, 1.068)
IMD4 ²	-	-	-	-	1.013	(0.962, 1.064)	1.016	(0.962, 1.073)
IMD5 ²	-	-	-	-	1.018	(0.968, 1.072)	1.013	(0.958, 1.073)
Days Difference ³	-	-	-	-	1.002	(0.990, 1.014)	1.007	(0.988, 1.026)
Number of Cases ⁴	-	-	-	-	1.102	(1.089, 1.116)	1.098	(1.072, 1.125)
Total ICU Beds ⁵	-	-	-	-	0.935	(0.923, 0.947)	0.982	(0.963, 1.002)
Temperature ⁶	-	-	-	-	0.893	(0.875, 0.912)	0.951	(0.907, 0.998)
Relative Humidity ⁷	-	-	-	-	0.827	(0.815, 0.839)	0.918	(0.876, 0.96)
log Population ⁸	-	-	-	-	0.967	(0.954, 0.98)	0.989	(0.975, 1.004)
Urban ⁹	-	-	-	-	1.110	(1.065, 1.159)	1.013	(0.964, 1.065)
High risk occupation ¹⁰	-	-	-	-	0.998	(0.984, 1.013)	0.999	(0.982, 1.017)
Smoking ¹¹	-	-	-	-	1.038	(1.021, 1.055)	1.037	(1.011, 1.065)
Obesity ¹²	-	-	-	-	1.021	(1.004, 1.036)	1.010	(0.984, 1.035)
τ^{13}	-	-	7.945	(6.930, 9.135)	-	-	8.958	(7.722, 10.434)
ϕ^{14}	-	-	0.991	(0.948, 0.999)	-	-	0.989	(0.936, 0.998)

Abbreviations: CrI, Credibility intervals; IMD, Index of Multiple Deprivation; ICU, Intensive Care Unit

¹ Population weighted modelled exposure to $PM_{2.5}$ as an average of 2014–2018 per 1km grid. The interpretation of the effect is for an increase of $1\mu g/m^3$ in the exposure.

² Quintiles of index of Multiple Deprivation without the air–quality domain by lower layer super output area as of 2019. The baseline category is the first, indicating most deprived areas, whereas the fifth category indicated the least deprived.

³ Days difference since first reported case per lower tier local authority, up to June 30, 2020. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the days i.e. 8.36 days.

⁴ Number of tested positive COVID–19 cases per lower tier local authority up to June 30, 2020. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the tested positive cases i.e. 957 cases.

⁵ Number of total ICU beds per population per NHS trust as of February 2020. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the number of beds per population i.e. 0.03 beds per population.

⁶ Modelled exposure to long-term (2014–2018) averaged temperature in 1km grid resolution. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the temperature i.e. $0.78^\circ C$.

⁷ Modelled exposure to long-term (2014–2018) average of hourly relative humidity over the year (%) in 1km grid resolution. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the relative humidity i.e. 2.34%.

⁸ Logged population estimates in 2018 by lower layer super output area. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the log population i.e. 0.21 log people.

⁹ Degrees of urbanicity as of 2011 by lower layer super output area. The baseline category is rural areas.

¹⁰ Proportion of workers (as of 2011) in high risk occupation by middle layer super output areas with exposure more than once per week with an infected person. The covariate was scaled and thus the interpretation of the effect is per standard

deviation of the proportion i.e. 1.5%.

¹¹ Smoking prevalence by general practitioner area in 2018–2019. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the prevalence i.e. 4.2.

¹² Obesity prevalence by general practitioner area in 2018–2019. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the prevalence i.e. 2.8.

¹³ The precision parameter of the spatial field as defined in Text S1.2.

¹⁴ The mixing parameter of the spatial field as defined in Text S1.2.

Table S6: **Sensitivity analysis** for long-term (2014–2018) averaged NO₂ exposure on COVID–19 mortality up to June 30, 2020 aggregated at the **lower tier local authority level**.

	Model 1		Model 2		Model 3		Model 4	
	Median	95% CrI	Median	95% CrI	Median	95% CrI	Median	95% CrI
Intercept	0.608	(0.592, 0.626)	0.509	(0.438, 0.590)	0.653	(0.615, 0.694)	0.689	(0.546, 0.868)
NO ₂ ¹	1.030	(1.029, 1.033)	1.038	(1.027, 1.048)	1.020	(1.016, 1.024)	1.018	(1.003, 1.035)
IMD2 ²	-	-	-	-	1.028	(0.988, 1.070)	0.981	(0.896, 1.075)
IMD3 ²	-	-	-	-	0.957	(0.916, 1.001)	0.930	(0.832, 1.040)
IMD4 ²	-	-	-	-	1.049	(0.998, 1.104)	0.969	(0.847, 1.111)
IMD5 ²	-	-	-	-	0.983	(0.923, 1.047)	0.932	(0.788, 1.103)
Days Difference ³	-	-	-	-	0.996	(0.982, 1.011)	1.019	(0.981, 1.059)
Number of Cases ⁴	-	-	-	-	1.156	(1.140, 1.174)	1.138	(1.080, 1.198)
Total ICU Beds ⁵	-	-	-	-	0.938	(0.928, 0.948)	0.952	(0.923, 0.983)
Temperature ⁶	-	-	-	-	0.943	(0.926, 0.959)	0.953	(0.868, 1.045)
Relative Humidity ⁷	-	-	-	-	0.874	(0.859, 0.888)	0.896	(0.829, 0.969)
log Population ⁸	-	-	-	-	0.850	(0.832, 0.868)	0.916	(0.862, 0.971)
Urban ⁹	-	-	-	-	1.110	(1.075, 1.147)	1.023	(0.939, 1.114)
High risk occupation ¹⁰	-	-	-	-	0.977	(0.965, 0.990)	0.971	(0.938, 1.006)
Smoking ¹¹	-	-	-	-	1.042	(1.023, 1.061)	1.087	(1.029, 1.147)
Obesity ¹²	-	-	-	-	1.048	(1.033, 1.064)	1.034	(0.988, 1.081)
τ ¹³	-	-	7.723	(6.318, 9.400)	-	-	9.719	(7.837, 11.969)
ϕ ¹⁴	-	-	0.946	(0.800, 0.989)	-	-	0.941	(0.798, 0.990)

Abbreviations: CrI, Credibility intervals; IMD, Index of Multiple Deprivation; ICU, Intensive Care Unit

¹ Population weighted modelled exposure to NO₂ as an average of 2014–2018 per 1km grid. The interpretation of the effect is for an increase of 1 $\mu\text{g}/\text{m}^3$ in the exposure.

² Quintiles of index of Multiple Deprivation without the air–quality domain by lower tier local authority as of 2019. The baseline category is the first, indicating most deprived areas, whereas the fifth category indicated the least deprived.

³ Days difference since first reported case per lower tier local authority, up to June 30, 2020. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the days i.e. 10.36 days.

⁴ Number of tested positive COVID–19 cases per lower tier local authority up to June 30, 2020. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the tested positive cases i.e. 643 cases.

⁵ Number of total ICU beds per population per NHS trust as of February 2020. The covariate was aggregated at lower tier local authority by population weighted average and then scaled. The interpretation of the effect is per standard deviation of the number of beds per population i.e. 0.02 beds per population.

⁶ Modelled exposure to long-term (2014–2018) averaged temperature in 1km grid resolution. The covariate was aggregated at lower tier local authority by population weighted average and then scaled. The interpretation of the effect is per standard deviation of the temperature i.e. 0.72 °C.

⁷ Modelled exposure to long-term (2014–2018) average of hourly relative humidity over the year (%) in 1km grid resolution. The covariate was aggregated at lower tier local authority by population weighted average and then scaled. The interpretation of the effect is per standard deviation of the relative humidity i.e. 2.13%.

⁸ Logged population estimates in 2018 by lower tier local authority. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the log population i.e. 0.61 log people.

⁹ Degrees of urbanicity as of 2011 by lower tier local authority. The baseline category is rural areas.

¹⁰ Proportion of workers (as of 2011) in high risk occupation by middle layer super output areas with exposure more than once per week with an infected person. The covariate was aggregated at lower tier local authority by population weighted average and then scaled. The interpretation of the effect is per standard deviation of the proportion i.e. 0.8%.

¹¹ Smoking prevalence by general practitioner area in 2018–2019. The covariate was aggregated at lower tier local authority by population weighted average and then scaled. The interpretation of the effect is per standard deviation of the prevalence i.e. 3.34.

¹² Obesity prevalence by general practitioner area in 2018–2019. The covariate was aggregated at lower tier local authority by population weighted average and then scaled. The interpretation of the effect is per standard deviation of the prevalence i.e. 2.23.

¹³ The precision parameter of the spatial field as defined in Text S1.2.

¹⁴ The mixing parameter of the spatial field as defined in Text S1.2.

Table S7: **Sensitivity analysis** for long-term (2014–2018) averaged $PM_{2.5}$ exposure on COVID–19 mortality up to June 30, 2020 aggregated at the **lower tier local authority level**.

	Model 1		Model 2		Model 3		Model 4	
	Median	95% CrI	Median	95% CrI	Median	95% CrI	Median	95% CrI
Intercept	0.087	(0.053, 0.142)	0.322	(0.108, 0.961)	0.298	(0.115, 0.734)	0.577	(0.139, 2.319)
$PM_{2.5}^1$	1.266	(1.21, 1.325)	1.067	(0.954, 1.191)	1.077	(0.988, 1.175)	0.996	(0.866, 1.145)
IMD2 ²	-	-	-	-	1.091	(0.779, 1.530)	1.040	(0.734, 1.467)
IMD3 ²	-	-	-	-	1.094	(0.779, 1.585)	1.047	(0.734, 1.540)
IMD4 ²	-	-	-	-	1.170	(0.794, 1.709)	1.089	(0.726, 1.617)
IMD5 ²	-	-	-	-	1.320	(0.899, 1.938)	1.138	(0.759, 1.708)
Days Difference ³	-	-	-	-	0.998	(0.916, 1.084)	1.065	(0.955, 1.183)
Number of Cases ⁴	-	-	-	-	1.332	(1.232, 1.439)	1.049	(0.927, 1.185)
Total ICU Beds ⁵	-	-	-	-	0.842	(0.759, 0.924)	0.905	(0.807, 1.002)
Temperature ⁶	-	-	-	-	1.077	(0.939, 1.232)	0.902	(0.688, 1.187)
Relative Humidity ⁷	-	-	-	-	0.895	(0.805, 0.998)	0.669	(0.533, 0.837)
log Population ⁸	-	-	-	-	0.931	(0.841, 1.028)	0.963	(0.867, 1.067)
Urban ⁹	-	-	-	-	1.178	(0.818, 1.727)	1.007	(0.667, 1.535)
High risk occupation ¹⁰	-	-	-	-	0.976	(0.884, 1.071)	0.999	(0.900, 1.103)
Smoking ¹¹	-	-	-	-	0.956	(0.841, 1.085)	0.972	(0.824, 1.140)
Obesity ¹²	-	-	-	-	0.962	(0.852, 1.088)	0.960	(0.829, 1.112)
τ^{13}	-	-	1.337	(0.883, 2.093)	-	-	1.529	(0.948, 2.602)
ϕ^{14}	-	-	0.897	(0.592, 0.987)	-	-	0.874	(0.528, 0.984)

Abbreviations: CrI, Credibility intervals; IMD, Index of Multiple Deprivation; ICU, Intensive Care Unit

¹ Population weighted modelled exposure to $PM_{2.5}$ as an average of 2014–2018 per 1km grid. The interpretation of the effect is for an increase of $1\mu g/m^3$ in the exposure.

² Quintiles of index of Multiple Deprivation without the air–quality domain by lower tier local authority as of 2019. The baseline category is the first, indicating most deprived areas, whereas the fifth category indicated the least deprived.

³ Days difference since first reported case per lower tier local authority, up to June 30, 2020. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the days i.e. 10.36 days.

⁴ Number of tested positive COVID–19 cases per lower tier local authority up to June 30, 2020. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the tested positive cases i.e. 643 cases.

⁵ Number of total ICU beds per population per NHS trust as of February 2020. The covariate was aggregated at lower tier local authority by population weighted average and then scaled. The interpretation of the effect is per standard deviation of the number of beds per population i.e. 0.02 beds per population.

⁶ Modelled exposure to long-term (2014–2018) averaged temperature in 1km grid resolution. The covariate was aggregated at lower tier local authority by population weighted average and then scaled. The interpretation of the effect is per standard deviation of the temperature i.e. $0.72^\circ C$.

⁷ Modelled exposure to long-term (2014–2018) average of hourly relative humidity over the year (%) in 1km grid resolution. The covariate was aggregated at lower tier local authority by population weighted average and then scaled. The interpretation of the effect is per standard deviation of the relative humidity i.e. 2.13%.

⁸ Logged population estimates in 2018 by lower tier local authority. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the log population i.e. 0.61 log people.

⁹ Degrees of urbanicity as of 2011 by lower tier local authority. The baseline category is rural areas.

¹⁰ Proportion of workers (as of 2011) in high risk occupation by middle layer super output areas with exposure more than once per week with an infected person. The covariate was aggregated at lower tier local authority by population weighted average and then scaled. The interpretation of the effect is per standard deviation of the proportion i.e. 0.8%.

¹¹ Smoking prevalence by general practitioner area in 2018–2019. The covariate was aggregated at lower tier local authority by population weighted average and then scaled. The interpretation of the effect is per standard deviation of the prevalence i.e. 3.34.

¹² Obesity prevalence by general practitioner area in 2018–2019. The covariate was aggregated at lower tier local authority by population weighted average and then scaled. The interpretation of the effect is per standard deviation of the prevalence i.e. 2.23.

¹³ The precision parameter of the spatial field as defined in Text S1.2.

¹⁴ The mixing parameter of the spatial field as defined in Text S1.2.

Table S8: **Sensitivity analysis** for long-term (2014–2018) averaged **NO₂** exposure on COVID–19 mortality up to March 23, 2020 (**pre-lockdown** period) at the lower layer super output area level.

	Model 1		Model 2		Model 3		Model 4	
	Median	95% CrI	Median	95% CrI	Median	95% CrI	Median	95% CrI
Intercept	0.392	(0.322, 0.477)	0.410	(0.284, 0.59)	0.457	(0.264, 0.768)	0.435	(0.230, 0.817)
NO ₂ ¹	1.053	(1.043, 1.062)	1.025	(1.003, 1.047)	1.019	(0.997, 1.041)	1.014	(0.984, 1.045)
IMD2 ²	-	-	-	-	1.098	(0.784, 1.542)	1.060	(0.747, 1.497)
IMD3 ²	-	-	-	-	1.108	(0.788, 1.609)	1.067	(0.747, 1.571)
IMD4 ²	-	-	-	-	1.182	(0.803, 1.728)	1.129	(0.753, 1.677)
IMD5 ²	-	-	-	-	1.331	(0.907, 1.954)	1.207	(0.803, 1.810)
Days Difference ³	-	-	-	-	0.991	(0.908, 1.077)	1.034	(0.932, 1.144)
Number of Cases ⁴	-	-	-	-	1.333	(1.233, 1.441)	1.254	(1.120, 1.404)
Total ICU Beds ⁵	-	-	-	-	0.837	(0.756, 0.917)	0.876	(0.777, 0.974)
Temperature ⁶	-	-	-	-	1.095	(0.968, 1.240)	0.891	(0.699, 1.141)
Relative Humidity ⁷	-	-	-	-	0.935	(0.827, 1.059)	0.833	(0.678, 1.022)
log Population ⁸	-	-	-	-	0.930	(0.840, 1.027)	0.953	(0.857, 1.057)
Urban ⁹	-	-	-	-	1.168	(0.808, 1.713)	1.009	(0.668, 1.530)
High risk occupation ¹⁰	-	-	-	-	0.972	(0.881, 1.066)	0.985	(0.887, 1.089)
Smoking ¹¹	-	-	-	-	0.942	(0.825, 1.073)	0.983	(0.833, 1.153)
Obesity ¹²	-	-	-	-	0.971	(0.860, 1.100)	0.948	(0.820, 1.098)
τ ¹³	-	-	1.432	(0.920, 2.326)	-	-	1.652	(0.994, 2.950)
ϕ ¹⁴	-	-	0.885	(0.557, 0.985)	-	-	0.863	(0.494, 0.983)

Abbreviations: CrI, Credibility intervals; IMD, Index of Multiple Deprivation; ICU, Intensive Care Unit

¹ Population weighted modelled exposure to NO₂ as an average of 2014–2018 per 1km grid. The interpretation of the effect is for an increase of 1 $\mu\text{g}/\text{m}^3$ in the exposure.

² Quintiles of index of Multiple Deprivation without the air-quality domain by lower layer super output area as of 2019. The baseline category is the first, indicating most deprived areas, whereas the fifth category indicated the least deprived.

³ Days difference since first reported case per lower tier local authority, up to March 23, 2020. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the days i.e. 8 days.

⁴ Number of tested positive COVID–19 cases per lower tier local authority up to March 23, 2020. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the tested positive cases i.e. 55 cases.

⁵ Number of total ICU beds per population per NHS trust as of February 2020. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the number of beds per population i.e. 0.02 beds per population.

⁶ Modelled exposure to long-term (2014–2018) averaged temperature in 1km grid resolution. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the temperature i.e. 0.74 °C.

⁷ Modelled exposure to long-term (2014–2018) average of hourly relative humidity over the year (%) in 1km grid resolution. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the relative humidity i.e. 1.81%.

⁸ Logged population estimates in 2018 by lower layer super output area. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the log population i.e. 427 log people.

⁸ Degrees of urbanicity as of 2011 by lower layer super output area. The baseline category is rural areas.

¹⁰ Proportion of workers (as of 2011) in high risk occupation by middle layer super output areas with exposure more than once per week with an infected person. The covariate was scaled and thus the interpretation of the effect is per standard

deviation of the proportion i.e. 0.8%.

¹¹ Smoking prevalence by general practitioner area in 2018–2019. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the prevalence i.e. 3.34.

¹² Smoking prevalence by general practitioner area in 2018–2019. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the prevalence i.e. 2.32.

¹³ The precision parameter of the spatial field as defined in Text S1.2.

¹⁴ The mixing parameter of the spatial field as defined in Text S1.2.

Table S9: **Sensitivity analysis** for long-term (2014–2018) averaged $PM_{2.5}$ exposure on COVID–19 mortality up to March 23, 2020 (**pre-lockdown** period) at the lower layer super output area level.

	Model 1		Model 2		Model 3		Model 4	
	Median	95% CrI	Median	95% CrI	Median	95% CrI	Median	95% CrI
Intercept	0.087	(0.053, 0.142)	0.322	(0.107, 0.962)	0.298	(0.115, 0.734)	0.443	(0.113, 1.689)
$PM_{2.5}^1$	1.266	(1.210, 1.325)	1.067	(0.954, 1.191)	1.077	(0.988, 1.175)	1.020	(0.891, 1.167)
IMD2 ²	-	-	-	-	1.091	(0.779, 1.530)	1.056	(0.744, 1.490)
IMD3 ²	-	-	-	-	1.094	(0.779, 1.585)	1.060	(0.742, 1.556)
IMD4 ²	-	-	-	-	1.170	(0.794, 1.709)	1.120	(0.746, 1.662)
IMD5 ²	-	-	-	-	1.320	(0.899, 1.938)	1.196	(0.795, 1.793)
Days Difference ³	-	-	-	-	0.998	(0.916, 1.084)	1.037	(0.934, 1.146)
Number of Cases ⁴	-	-	-	-	1.332	(1.232, 1.439)	1.262	(1.128, 1.412)
Total ICU Beds ⁵	-	-	-	-	0.842	(0.759, 0.924)	0.877	(0.778, 0.975)
Temperature ⁶	-	-	-	-	1.077	(0.939, 1.232)	0.907	(0.710, 1.163)
Relative Humidity ⁷	-	-	-	-	0.895	(0.805, 0.998)	0.808	(0.663, 0.984)
log Population ⁸	-	-	-	-	0.931	(0.841, 1.028)	0.957	(0.861, 1.060)
Urban ⁹	-	-	-	-	1.178	(0.818, 1.727)	1.028	(0.681, 1.563)
High risk occupation ¹⁰ -	-	-	-	0.976	(0.884, 1.071)	0.984	(0.885, 1.088)	
Smoking ¹¹	-	-	-	-	0.956	(0.841, 1.085)	0.993	(0.842, 1.164)
Obesity ¹²	-	-	-	-	0.962	(0.852, 1.088)	0.942	(0.815, 1.091)
τ^{13}	-	-	1.336	(0.882, 2.092)	-	-	1.624	(0.986, 2.864)
ϕ^{14}	-	-	0.897	(0.592, 0.987)	-	-	0.866	(0.504, 0.984)

Abbreviations: CrI, Credibility intervals; IMD, Index of Multiple Deprivation; ICU, Intensive Care Unit

¹ Population weighted modelled exposure to $PM_{2.5}$ as an average of 2014–2018 per 1km grid. The interpretation of the effect is for an increase of $1\mu g/m^3$ in the exposure.

² Quintiles of index of Multiple Deprivation without the air-quality domain by lower layer super output area as of 2019. The baseline category is the first, indicating most deprived areas, whereas the fifth category indicated the least deprived.

³ Days difference since first reported case per lower tier local authority, up to March 23, 2020. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the days i.e. 8 days.

⁴ Number of tested positive COVID–19 cases per lower tier local authority up to March 23, 2020. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the tested positive cases i.e. 55 cases.

⁵ Number of total ICU beds per population per NHS trust as of February 2020. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the number of beds per population i.e. 0.02 beds per population.

⁶ Modelled exposure to long-term (2014–2018) averaged temperature in 1km grid resolution. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the temperature i.e. $0.74^\circ C$.

⁷ Modelled exposure to long-term (2014–2018) average of hourly relative humidity over the year (%) in 1km grid resolution. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the relative humidity i.e. 1.81%.

⁸ Logged population estimates in 2018 by lower layer super output area. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the log population i.e. 427 log people.

⁸ Degrees of urbanicity as of 2011 by lower layer super output area. The baseline category is rural areas.

¹⁰ Proportion of workers (as of 2011) in high risk occupation by middle layer super output areas with exposure more than once per week with an infected person. The covariate was scaled and thus the interpretation of the effect is per standard

deviation of the proportion i.e. 0.8%.

¹¹ Smoking prevalence by general practitioner area in 2018–2019. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the prevalence i.e. 3.34.

¹² Smoking prevalence by general practitioner area in 2018–2019. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the prevalence i.e. 2.32.

¹³ The precision parameter of the spatial field as defined in Text S1.2.

¹⁴ The mixing parameter of the spatial field as defined in Text S1.2.

Table S10: **Sensitivity analysis** for long-term (2014–2018) averaged **NO₂** exposure on **suspected COVID–19** deaths up to June 30, 2020 at the lower layer super output area level.

	Model 1		Model 2		Model 3		Model 4	
	Median	95% CrI	Median	95% CrI	Median	95% CrI	Median	95% CrI
Intercept	0.659	(0.644, 0.675)	0.783	(0.727, 0.842)	0.729	(0.685, 0.776)	0.886	(0.797, 0.990)
NO ₂ ¹	1.026	(1.025, 1.028)	1.012	(1.007, 1.016)	1.014	(1.011, 1.017)	1.003	(0.997, 1.009)
IMD2 ²	-	-	-	-	1.020	(0.980, 1.064)	1.010	(0.968, 1.056)
IMD3 ²	-	-	-	-	1.003	(0.963, 1.047)	1.011	(0.967, 1.059)
IMD4 ²	-	-	-	-	1.028	(0.986, 1.075)	1.016	(0.971, 1.066)
IMD5 ²	-	-	-	-	1.043	(0.997, 1.093)	1.013	(0.963, 1.067)
Days Difference ³	-	-	-	-	1.014	(1.004, 1.024)	1.012	(0.994, 1.030)
Number of Cases ⁴	-	-	-	-	1.096	(1.084, 1.108)	1.104	(1.080, 1.129)
Total ICU Beds ⁵	-	-	-	-	0.937	(0.927, 0.947)	0.984	(0.966, 1.002)
Temperature ⁶	-	-	-	-	0.927	(0.913, 0.940)	0.950	(0.911, 0.991)
Relative Humidity ⁷	-	-	-	-	0.861	(0.848, 0.874)	0.907	(0.867, 0.947)
log Population ⁸	-	-	-	-	0.968	(0.955, 0.981)	0.989	(0.975, 1.003)
Urban ⁹	-	-	-	-	1.081	(1.041, 1.123)	1.011	(0.966, 1.057)
High risk occupation ¹⁰	-	-	-	-	0.991	(0.980, 1.003)	1.000	(0.985, 1.016)
Smoking ¹¹	-	-	-	-	1.009	(0.995, 1.023)	1.025	(1.003, 1.047)
Obesity ¹²	-	-	-	-	1.010	(0.996, 1.023)	1.006	(0.983, 1.029)
τ ¹³	-	-	8.83	(7.78, 10.028)	-	-	9.903	(8.647, 11.369)
ϕ ¹⁴	-	-	0.992	(0.957, 0.999)	-	-	0.991	(0.951, 0.999)

Abbreviations: CrI, Credibility intervals; IMD, Index of Multiple Deprivation; ICU, Intensive Care Unit

¹ Population weighted modelled exposure to NO₂ as an average of 2014–2018 per 1km grid. The interpretation of the effect is for an increase of 1 $\mu\text{g}/\text{m}^3$ in the exposure.

² Quintiles of index of Multiple Deprivation without the air-quality domain by lower layer super output area as of 2019. The baseline category is the first, indicating most deprived areas, whereas the fifth category indicated the least deprived.

³ Days difference since first reported case per lower tier local authority, up to June 30, 2020. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the days i.e. 8.36 days.

⁴ Number of tested positive COVID–19 cases per lower tier local authority up to June 30, 2020. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the tested positive cases i.e. 957 cases.

⁵ Number of total ICU beds per population per NHS trust as of February 2020. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the number of beds per population i.e. 0.03 beds per population.

⁶ Modelled exposure to long-term (2014–2018) averaged temperature in 1km grid resolution. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the temperature i.e. 0.78 °C.

⁷ Modelled exposure to long-term (2014–2018) average of hourly relative humidity over the year (%) in 1km grid resolution. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the relative humidity i.e. 2.34%.

⁸ Logged population estimates in 2018 by lower layer super output area. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the log population i.e. 0.21 log people.

⁸ Degrees of urbanicity as of 2011 by lower layer super output area. The baseline category is rural areas.

¹⁰ Proportion of workers (as of 2011) in high risk occupation by middle layer super output areas with exposure more than once per week with an infected person. The covariate was scaled and thus the interpretation of the effect is per standard

deviation of the proportion i.e. 1.5%.

¹¹ Smoking prevalence by general practitioner area in 2018–2019. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the prevalence i.e. 4.2.

¹² Obesity prevalence by general practitioner area in 2018–2019. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the prevalence i.e. 2.8.

¹³ The precision parameter of the spatial field as defined in Text S1.2.

¹⁴ The mixing parameter of the spatial field as defined in Text S1.2.

Table S11: **Sensitivity analysis** for long-term (2014–2018) averaged $PM_{2.5}$ exposure on **suspected** COVID–19 deaths up to June 30, 2020 at the lower layer super output area level.

	Model 1		Model 2		Model 3		Model 4	
	Median	95% CrI	Median	95% CrI	Median	95% CrI	Median	95% CrI
Intercept	0.599	(0.566, 0.634)	0.598	(0.467, 0.761)	0.615	(0.550, 0.688)	0.868	(0.638, 1.179)
$PM_{2.5}^1$	1.054	(1.048, 1.060)	1.048	(1.022, 1.074)	1.040	(1.029, 1.051)	1.007	(0.976, 1.039)
IMD2 ²	-	-	-	-	1.016	(0.976, 1.060)	1.010	(0.968, 1.056)
IMD3 ²	-	-	-	-	0.991	(0.952, 1.036)	1.010	(0.967, 1.058)
IMD4 ²	-	-	-	-	1.015	(0.973, 1.061)	1.015	(0.971, 1.066)
IMD5 ²	-	-	-	-	1.027	(0.983, 1.076)	1.012	(0.962, 1.066)
Days Difference ³	-	-	-	-	1.017	(1.007, 1.027)	1.012	(0.994, 1.030)
Number of Cases ⁴	-	-	-	-	1.102	(1.090, 1.114)	1.104	(1.080, 1.129)
Total ICU Beds ⁵	-	-	-	-	0.939	(0.929, 0.949)	0.984	(0.966, 1.002)
Temperature ⁶	-	-	-	-	0.919	(0.903, 0.935)	0.952	(0.913, 0.993)
Relative Humidity ⁷	-	-	-	-	0.831	(0.821, 0.842)	0.901	(0.863, 0.940)
log Population ⁸	-	-	-	-	0.969	(0.956, 0.982)	0.990	(0.976, 1.004)
Urban ⁹	-	-	-	-	1.107	(1.068, 1.149)	1.013	(0.969, 1.059)
High risk occupation ¹⁰	-	-	-	-	0.994	(0.983, 1.007)	1.000	(0.985, 1.016)
Smoking ¹¹	-	-	-	-	1.019	(1.004, 1.033)	1.026	(1.003, 1.048)
Obesity ¹²	-	-	-	-	1.006	(0.992, 1.020)	1.005	(0.982, 1.029)
τ^{13}	-	-	8.667	(7.649, 9.826)	-	-	9.884	(8.631, 11.346)
ϕ^{14}	-	-	0.993	(0.959, 0.999)	-	-	0.991	(0.952, 0.999)

Abbreviations: CrI, Credibility intervals; IMD, Index of Multiple Deprivation; ICU, Intensive Care Unit

¹ Population weighted modelled exposure to $PM_{2.5}$ as an average of 2014–2018 per 1km grid. The interpretation of the effect is for an increase of $1\mu g/m^3$ in the exposure.

² Quintiles of index of Multiple Deprivation without the air–quality domain by lower layer super output area as of 2019. The baseline category is the first, indicating most deprived areas, whereas the fifth category indicated the least deprived.

³ Days difference since first reported case per lower tier local authority, up to June 30, 2020. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the days i.e. 8.36 days.

⁴ Number of tested positive COVID–19 cases per lower tier local authority up to June 30, 2020. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the tested positive cases i.e. 957 cases.

⁵ Number of total ICU beds per population per NHS trust as of February 2020. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the number of beds per population i.e. 0.03 beds per population.

⁶ Modelled exposure to long-term (2014–2018) averaged temperature in 1km grid resolution. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the temperature i.e. $0.78^\circ C$.

⁷ Modelled exposure to long-term (2014–2018) average of hourly relative humidity over the year (%) in 1km grid resolution. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the relative humidity i.e. 2.34%.

⁸ Logged population estimates in 2018 by lower layer super output area. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the log population i.e. 0.21 log people.

⁸ Degrees of urbanicity as of 2011 by lower layer super output area. The baseline category is rural areas.

¹⁰ Proportion of workers (as of 2011) in high risk occupation by middle layer super output areas with exposure more than once per week with an infected person. The covariate was scaled and thus the interpretation of the effect is per standard

deviation of the proportion i.e. 1.5%.

¹¹ Smoking prevalence by general practitioner area in 2018–2019. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the prevalence i.e. 4.2.

¹² Obesity prevalence by general practitioner area in 2018–2019. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the prevalence i.e. 2.8.

¹³ The precision parameter of the spatial field as defined in Text S1.2.

¹⁴ The mixing parameter of the spatial field as defined in Text S1.2.

Table S12: **Sensitivity analysis** for long-term (2014–2018) averaged NO₂ (**zero-inflated Poisson model**) exposure on confirmed COVID–19 deaths up to June 30, 2020 at the lower layer super output area level.

	Model 1		Model 2		Model 3		Model 4	
	Median	95% CrI	Median	95% CrI	Median	95% CrI	Median	95% CrI
Intercept	0.769	(0.736, 0.803)	0.759	(0.683, 0.840)	0.778	(0.698, 0.866)	0.853	(0.725, 1.004)
NO ₂ ¹	1.021	(1.018, 1.023)	1.014	(1.007, 1.020)	1.015	(1.010, 1.020)	1.006	(0.997, 1.015)
IMD2 ²	-	-	-	-	1.020	(0.956, 1.091)	1.014	(0.947, 1.088)
IMD3 ²	-	-	-	-	1.007	(0.945, 1.075)	1.015	(0.948, 1.085)
IMD4 ²	-	-	-	-	1.019	(0.947, 1.092)	1.017	(0.942, 1.094)
IMD5 ²	-	-	-	-	1.017	(0.944, 1.089)	1.015	(0.937, 1.094)
Days Difference ³	-	-	-	-	0.998	(0.979, 1.017)	1.009	(0.981, 1.036)
Number of Cases ⁴	-	-	-	-	1.077	(1.056, 1.098)	1.081	(1.049, 1.114)
Total ICU Beds ⁵	-	-	-	-	0.943	(0.924, 0.962)	0.982	(0.955, 1.009)
Temperature ⁶	-	-	-	-	0.912	(0.888, 0.937)	0.943	(0.883, 1.006)
Relative Humidity ⁷	-	-	-	-	0.887	(0.863, 0.911)	0.925	(0.867, 0.985)
log Population ⁸	-	-	-	-	0.966	(0.946, 0.985)	0.988	(0.967, 1.008)
Urban ⁹	-	-	-	-	1.071	(1.011, 1.143)	1.006	(0.942, 1.078)
High risk occupation ¹⁰	-	-	-	-	1.002	(0.981, 1.021)	1.000	(0.977, 1.025)
Smoking ¹¹	-	-	-	-	1.037	(1.012, 1.063)	1.042	(1.009, 1.076)
Obesity ¹²	-	-	-	-	1.013	(0.990, 1.036)	1.009	(0.976, 1.042)
τ ¹³	-	-	8.108	(6.551, 13.798)	-	-	8.966	(7.204, 13.122)
ϕ ¹⁴	-	-	0.967	(0.900, 0.999)	-	-	0.976	(0.897, 1.000)

Abbreviations: CrI, Credibility intervals; IMD, Index of Multiple Deprivation; ICU, Intensive Care Unit

¹ Population weighted modelled exposure to NO₂ and as an average of 2014–2018 per 1km grid. The interpretation of the effect is for an increase of 1 $\mu\text{g}/\text{m}^3$ in the exposure.

² Quintiles of index of Multiple Deprivation without the air–quality domain by lower layer super output area as of 2019. The baseline category is the first, indicating most deprived areas, whereas the fifth category indicated the least deprived.

³ Days difference since first reported case per lower tier local authority, up to June 30, 2020. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the days i.e. 8.36 days.

⁴ Number of tested positive COVID–19 cases per lower tier local authority up to June 30, 2020. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the tested positive cases i.e. 957 cases.

⁵ Number of total ICU beds per population per NHS trust as of February 2020. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the number of beds per population i.e. 0.03 beds per population.

⁶ Modelled exposure to long–term (2014–2018) averaged temperature in 1km grid resolution. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the temperature i.e. 0.78 °C.

⁷ Modelled exposure to long–term (2014–2018) average of hourly relative humidity over the year (%) in 1km grid resolution. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the relative humidity i.e. 2.34%.

⁸ Logged population estimates in 2018 by lower layer super output area. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the log population i.e. 0.21 log people.

⁸ Degrees of urbanicity as of 2011 by lower layer super output area. The baseline category is rural areas.

¹⁰ Proportion of workers (as of 2011) in high risk occupation by middle layer super output areas with exposure more than once per week with an infected person. The covariate was scaled and thus the interpretation of the effect is per standard

deviation of the proportion i.e. 1.5%.

¹¹ Smoking prevalence by general practitioner area in 2018–2019. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the prevalence i.e. 4.2.

¹² Obesity prevalence by general practitioner area in 2018–2019. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the prevalence i.e. 2.8.

¹³ The precision parameter of the spatial field as defined in Text S1.2.

¹⁴ The mixing parameter of the spatial field as defined in Text S1.2.

Table S13: **Sensitivity analysis** for long-term (2014–2018) averaged PM_{2.5} (**zero-inflated Poisson model**) exposure on confirmed COVID–19 deaths up to June 30, 2020 at the lower layer super output area level.

	Model 1		Model 2		Model 3		Model 4	
	Median	95% CrI	Median	95% CrI	Median	95% CrI	Median	95% CrI
Intercept	0.832	(0.749, 0.926)	0.537	(0.378, 0.76)	0.702	(0.566, 0.857)	0.797	(0.516, 1.248)
PM _{2.5} ¹	1.026	(1.015, 1.037)	1.059	(1.022, 1.098)	1.034	(1.014, 1.055)	1.016	(0.972, 1.061)
IMD2 ²	-	-	-	-	1.015	(0.952, 1.086)	1.012	(0.946, 1.086)
IMD3 ²	-	-	-	-	0.994	(0.932, 1.061)	1.013	(0.946, 1.084)
IMD4 ²	-	-	-	-	1.003	(0.933, 1.075)	1.015	(0.94, 1.092)
IMD5 ²	-	-	-	-	0.999	(0.928, 1.069)	1.013	(0.935, 1.091)
Days Difference ³	-	-	-	-	1.002	(0.983, 1.021)	1.009	(0.981, 1.036)
Number of Cases ⁴	-	-	-	-	1.082	(1.061, 1.102)	1.081	(1.049, 1.114)
Total ICU Beds ⁵	-	-	-	-	0.944	(0.925, 0.963)	0.983	(0.956, 1.01)
Temperature ⁶	-	-	-	-	0.91	(0.879, 0.939)	0.946	(0.886, 1.011)
Relative Humidity ⁷	-	-	-	-	0.855	(0.835, 0.874)	0.915	(0.862, 0.971)
log Population ⁸	-	-	-	-	0.967	(0.947, 0.986)	0.988	(0.967, 1.009)
Urban ⁹	-	-	-	-	1.101	(1.04, 1.173)	1.011	(0.948, 1.083)
High risk occupation ¹⁰	-	-	-	-	1.003	(0.982, 1.023)	1.000	(0.977, 1.025)
Smoking ¹¹	-	-	-	-	1.047	(1.022, 1.072)	1.043	(1.01, 1.078)
Obesity ¹²	-	-	-	-	1.009	(0.986, 1.032)	1.008	(0.975, 1.041)
τ ¹³	-	-	7.859	(6.363, 13.277)	-	-	8.908	(7.168, 12.719)
ϕ ¹⁴	-	-	0.967	(0.904, 0.992)	-	-	0.974	(0.900, 1.000)

Abbreviations: CrI, Credibility intervals; IMD, Index of Multiple Deprivation; ICU, Intensive Care Unit

¹ Population weighted modelled exposure to PM_{2.5} and as an average of 2014–2018 per 1km grid. The interpretation of the effect is for an increase of 1 $\mu\text{g}/\text{m}^3$ in the exposure.

² Quintiles of index of Multiple Deprivation without the air–quality domain by lower layer super output area as of 2019. The baseline category is the first, indicating most deprived areas, whereas the fifth category indicated the least deprived.

³ Days difference since first reported case per lower tier local authority, up to June 30, 2020. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the days i.e. 8.36 days.

⁴ Number of tested positive COVID–19 cases per lower tier local authority up to June 30, 2020. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the tested positive cases i.e. 957 cases.

⁵ Number of total ICU beds per population per NHS trust as of February 2020. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the number of beds per population i.e. 0.03 beds per population.

⁶ Modelled exposure to long-term (2014–2018) averaged temperature in 1km grid resolution. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the temperature i.e. 0.78 °C.

⁷ Modelled exposure to long-term (2014–2018) average of hourly relative humidity over the year (%) in 1km grid resolution. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the relative humidity i.e. 2.34%.

⁸ Logged population estimates in 2018 by lower layer super output area. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the log population i.e. 0.21 log people.

⁸ Degrees of urbanicity as of 2011 by lower layer super output area. The baseline category is rural areas.

¹⁰ Proportion of workers (as of 2011) in high risk occupation by middle layer super output areas with exposure more than once per week with an infected person. The covariate was scaled and thus the interpretation of the effect is per standard

deviation of the proportion i.e. 1.5%.

¹¹ Smoking prevalence by general practitioner area in 2018–2019. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the prevalence i.e. 4.2.

¹² Obesity prevalence by general practitioner area in 2018–2019. The covariate was scaled and thus the interpretation of the effect is per standard deviation of the prevalence i.e. 2.8.

¹³ The precision parameter of the spatial field as defined in Text S1.2.

¹⁴ The mixing parameter of the spatial field as defined in Text S1.2.

Figures

Figure S1: Boundaries of the Lower Tier Local Authorities of England in 2019.

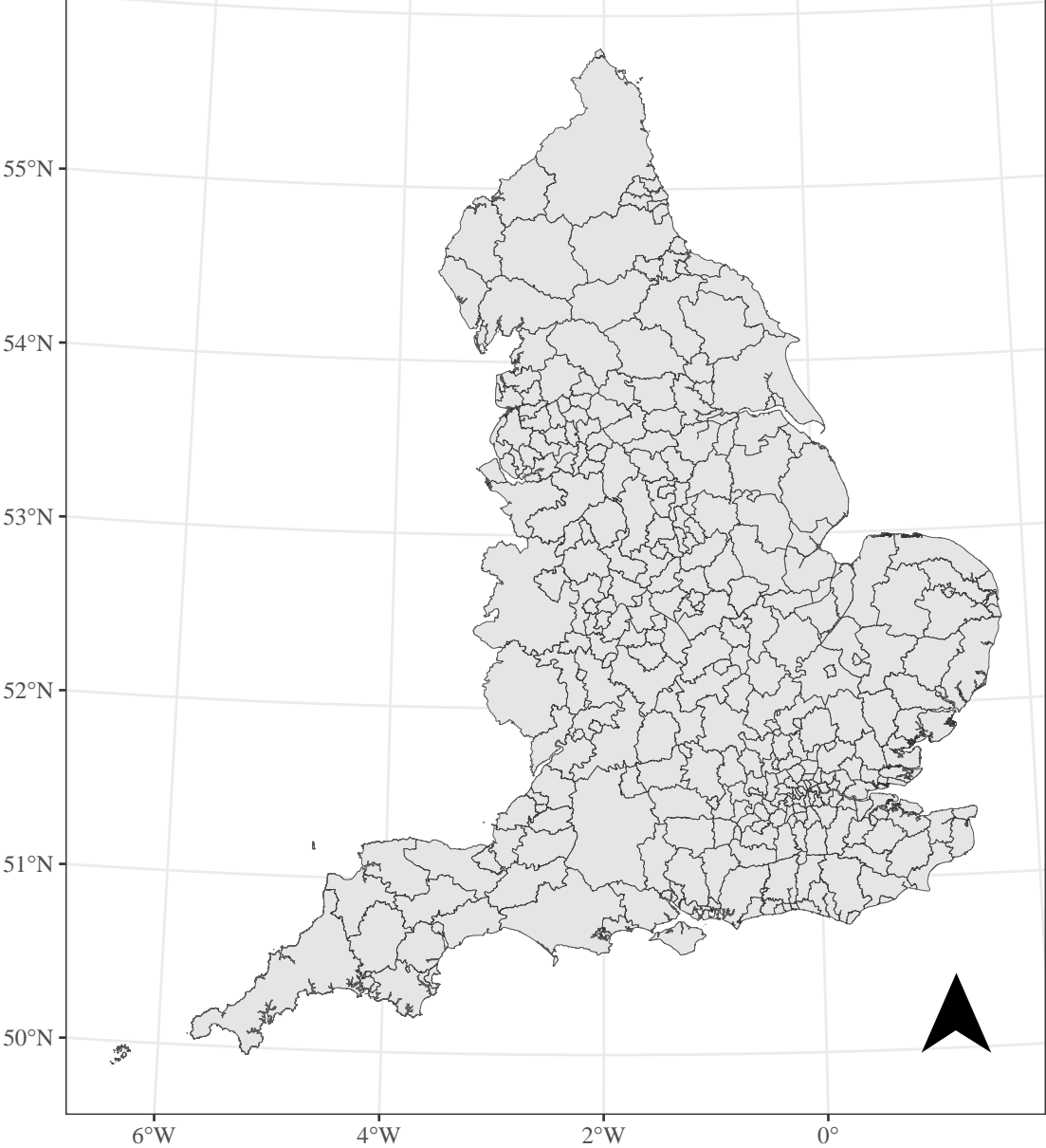


Figure S2: Boundaries of the Lower Layer Super Output Areas of England in 2011.

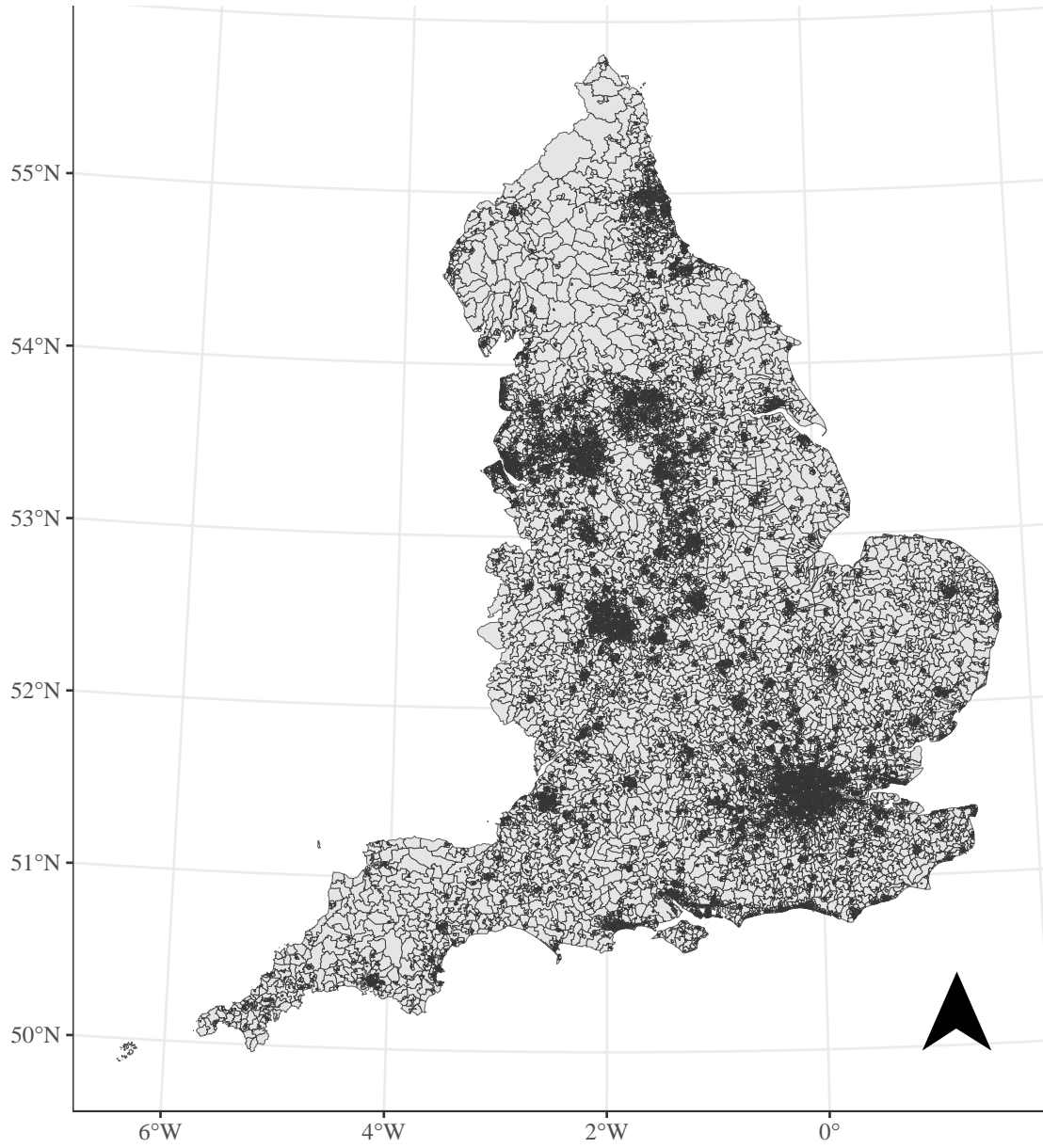


Figure S3: Total population by Lower Layer Super Output Areas (LSOAs) and urbanicity in England in 2018. The red dashed line is the median of total population by LSOA.

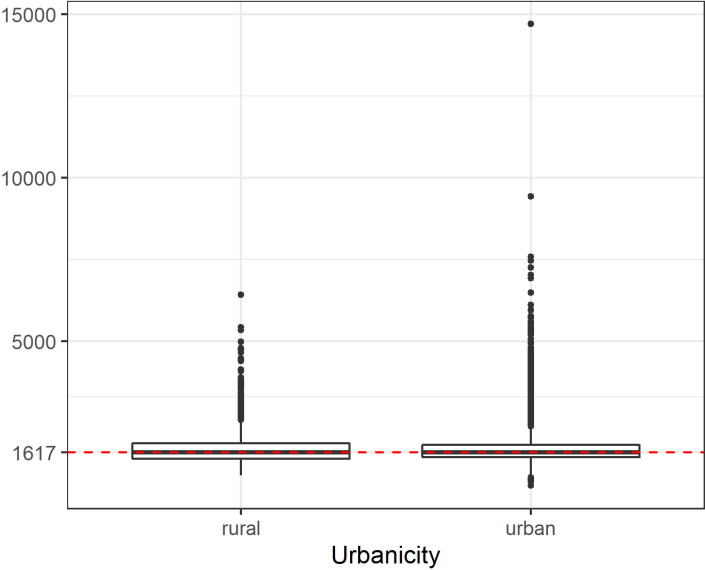


Figure S4: Mean and median NO₂ and PM_{2.5} concentration per Lower Layer Super Output Areas of England averaged over 2014-2018.

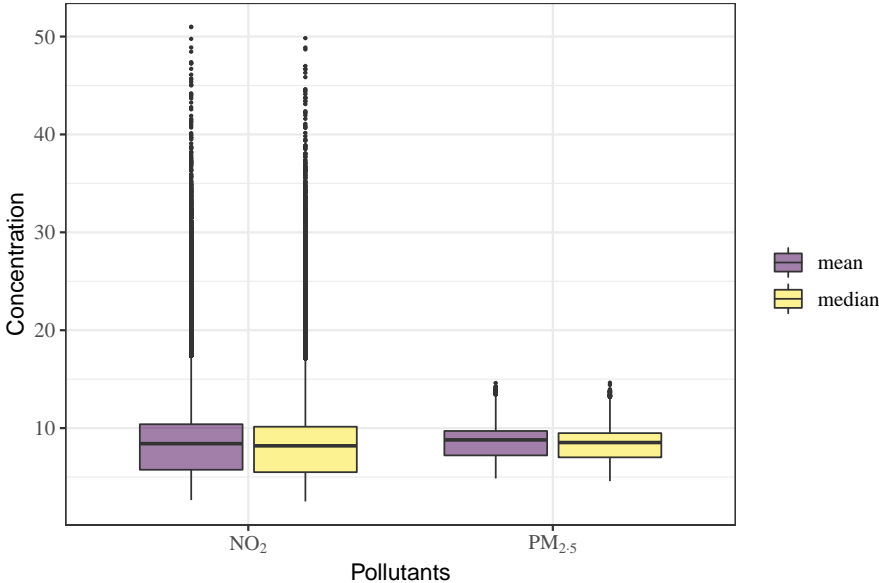


Figure S5: Scatterplot of averaged concentration of NO_2 and $\text{PM}_{2.5}$ during 2014-2018 in England.

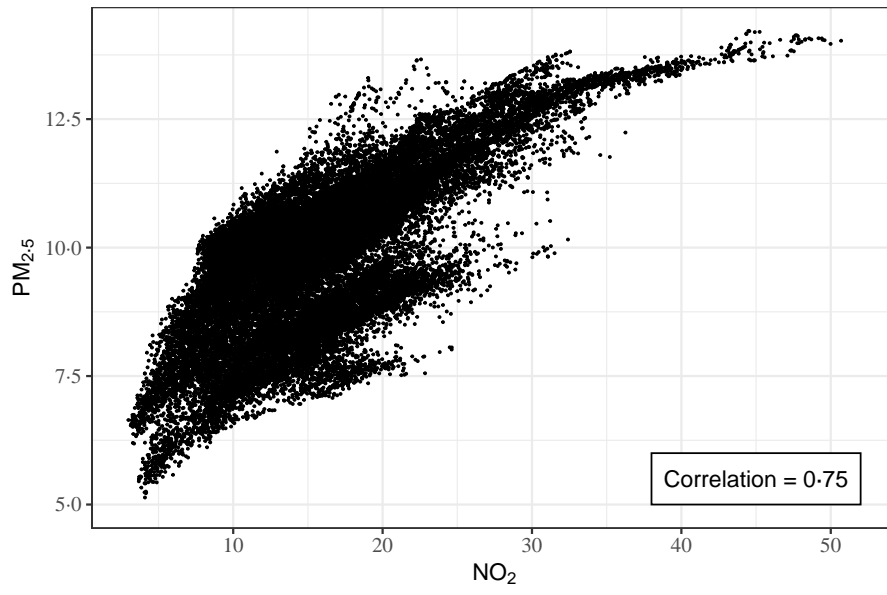


Figure S6: Left: The distribution of the median frequency of number of confirmed COVID-19 deaths up to June 30. Right: Proportion of zeros across the different samples.

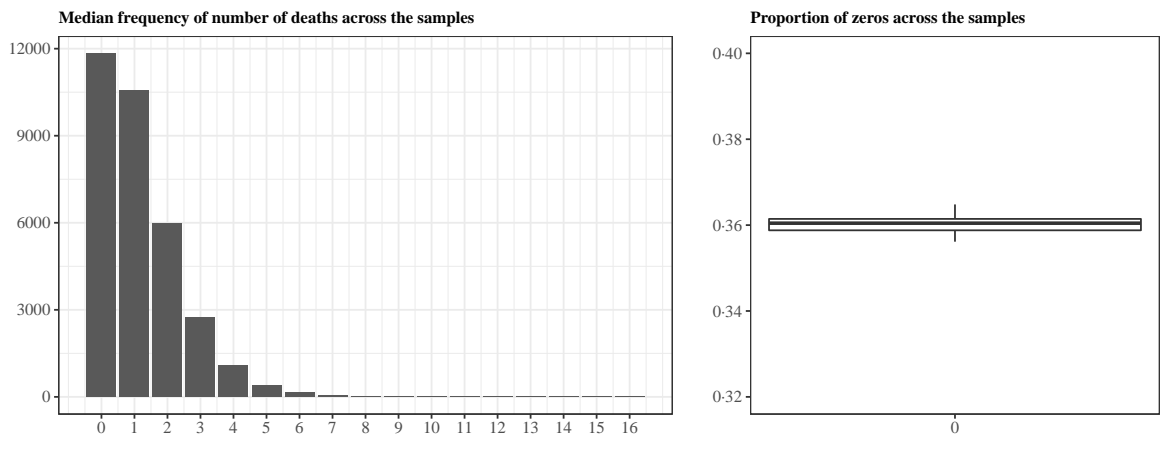


Figure S7: Map and boxplot of the modelled averaged during 2014–2018 exposure to **temperature** ($^{\circ}\text{C}$) at the lower layer super output area level.

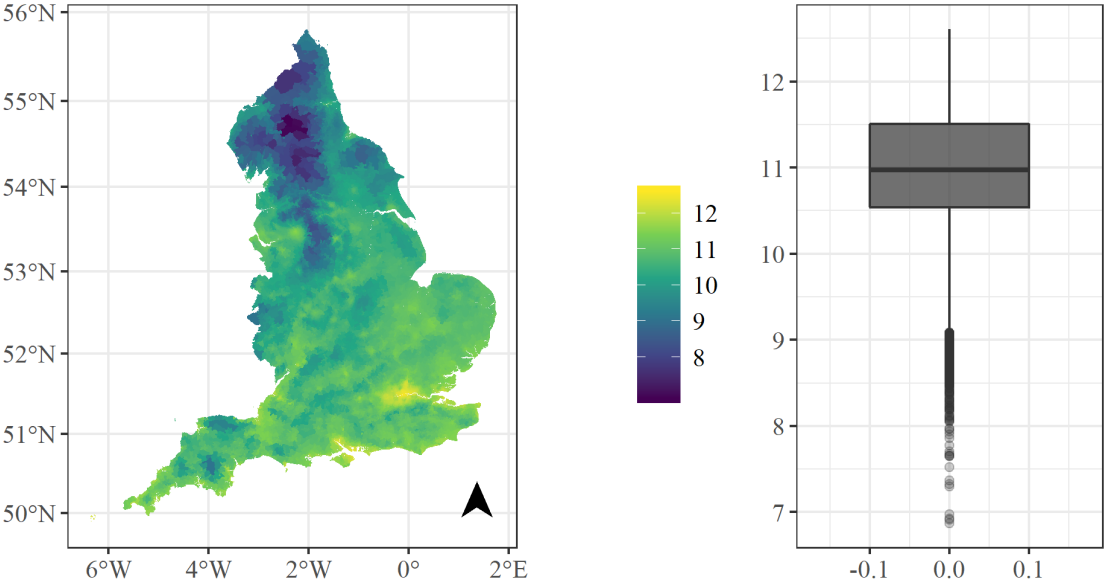


Figure S8: Map and boxplot of the modelled averaged during 2014–2018 exposure to **relative humidity (%)** at the lower layer super output area level.

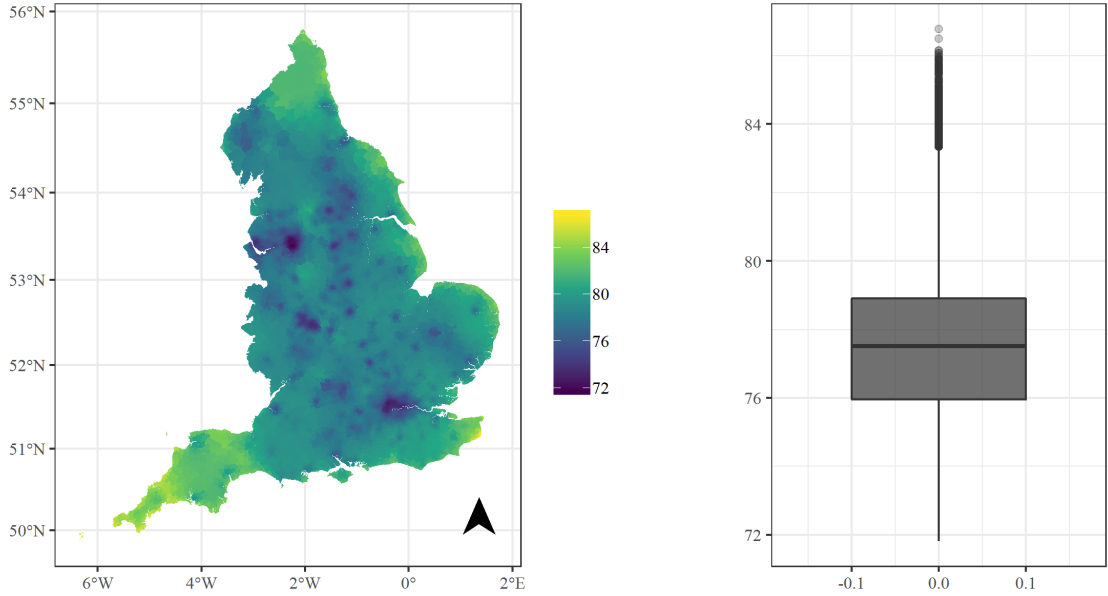


Figure S9: Map of Quintiles of the **Index of Multiple Deprivation (IMD)** without air-quality domain at the lower layer super output area level as of 2011 and boxplot of the corresponding raw score.

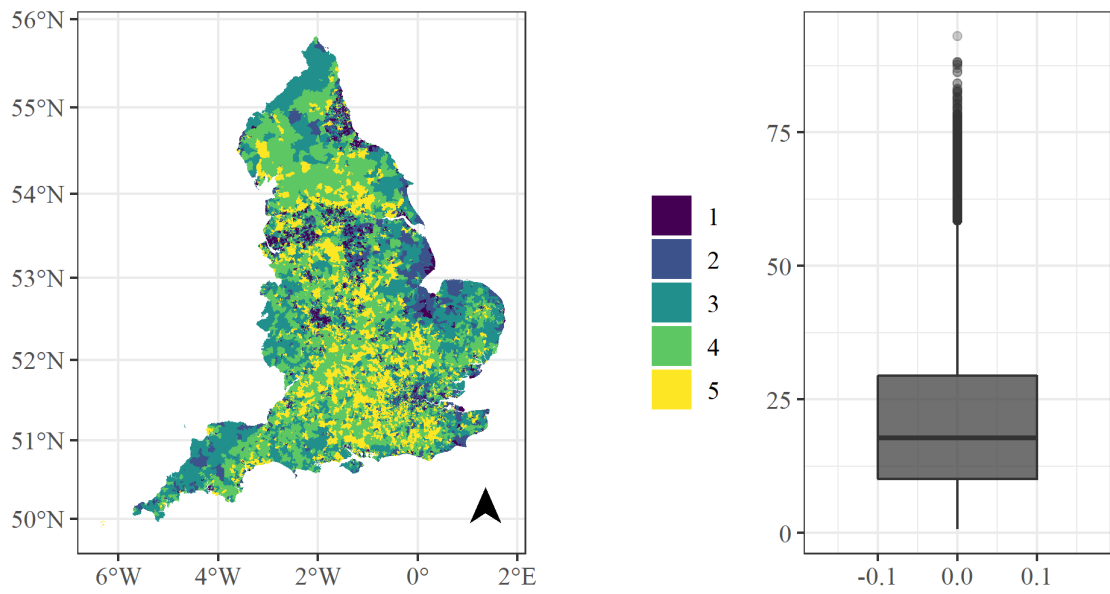


Figure S10: Map and barchart of the **urban and rural areas** in England at the lower layer super output area level as of 2011.

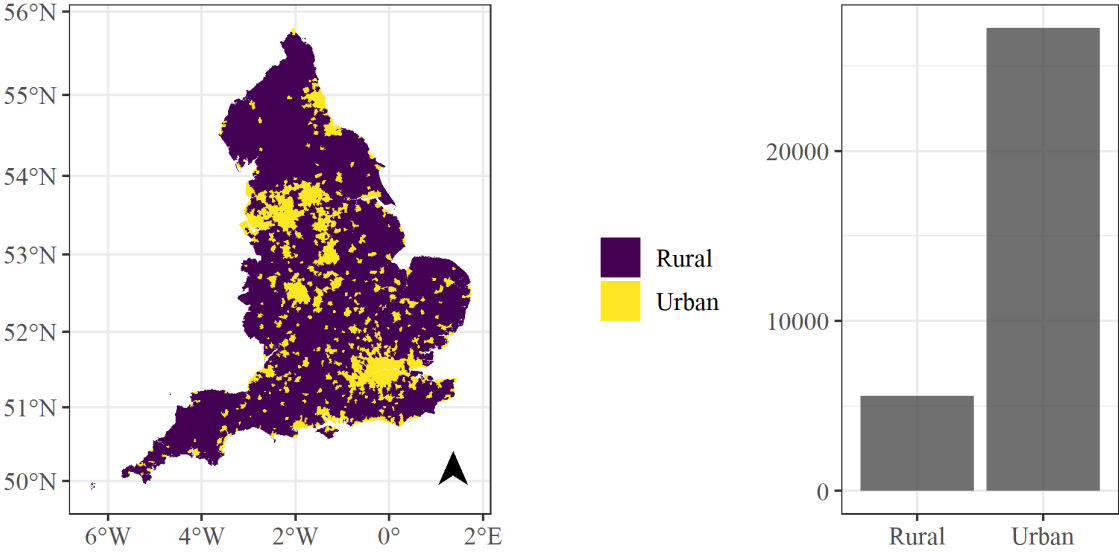


Figure S11: Map and boxplot of the proportion of people employed in **occupations with high risk of exposure** to COVID-19 at the middle layer super output area level level as of 2011.

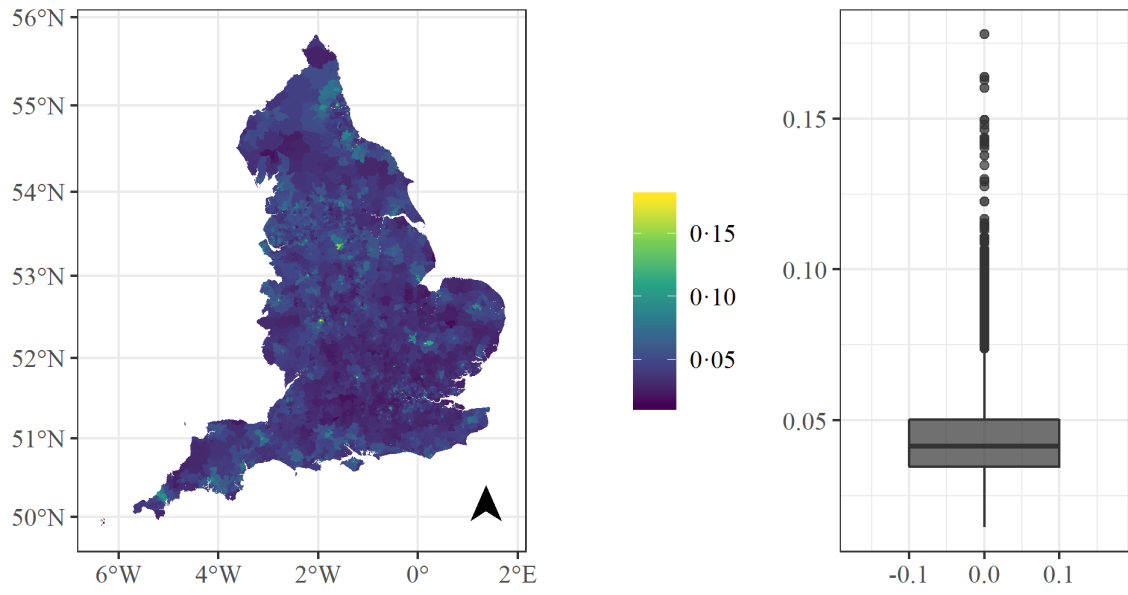


Figure S12: Map and barchart of **days difference since first reported COVID-19 positive test** per lower tier local authority, up to June 30, 2020.

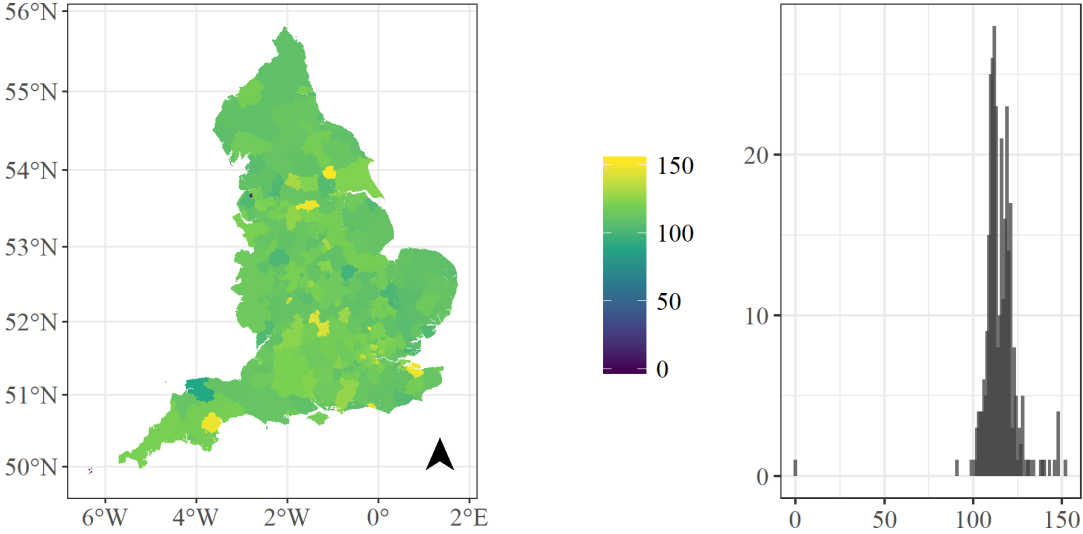


Figure S13: Map and barchart of the **number of tested positive COVID-19 cases** per lower tier local authority as of 30-th June 2020.

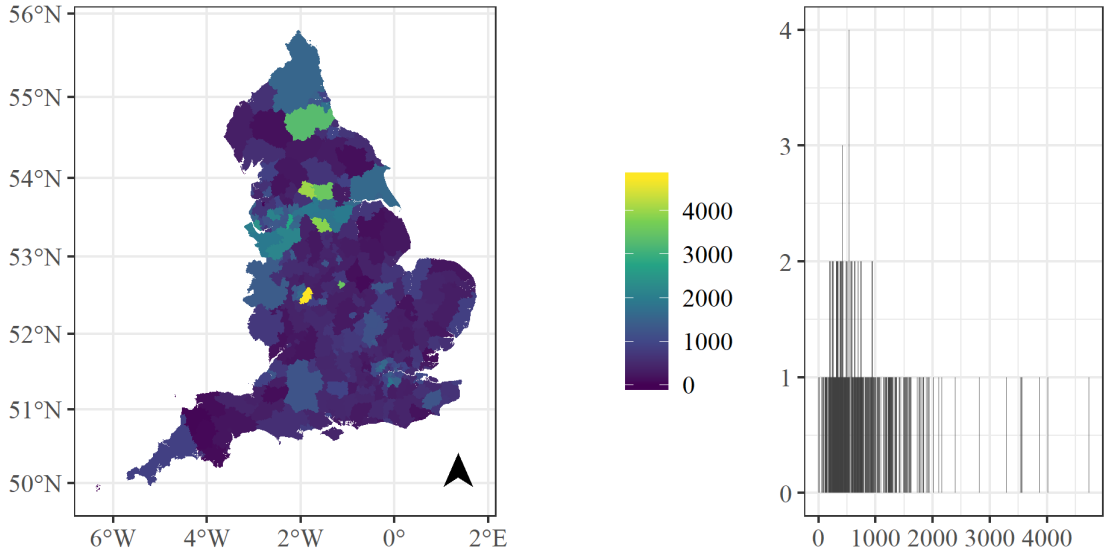


Figure S14: Map and boxplot of **log population** distribution per lower layer super output area as of 2018.

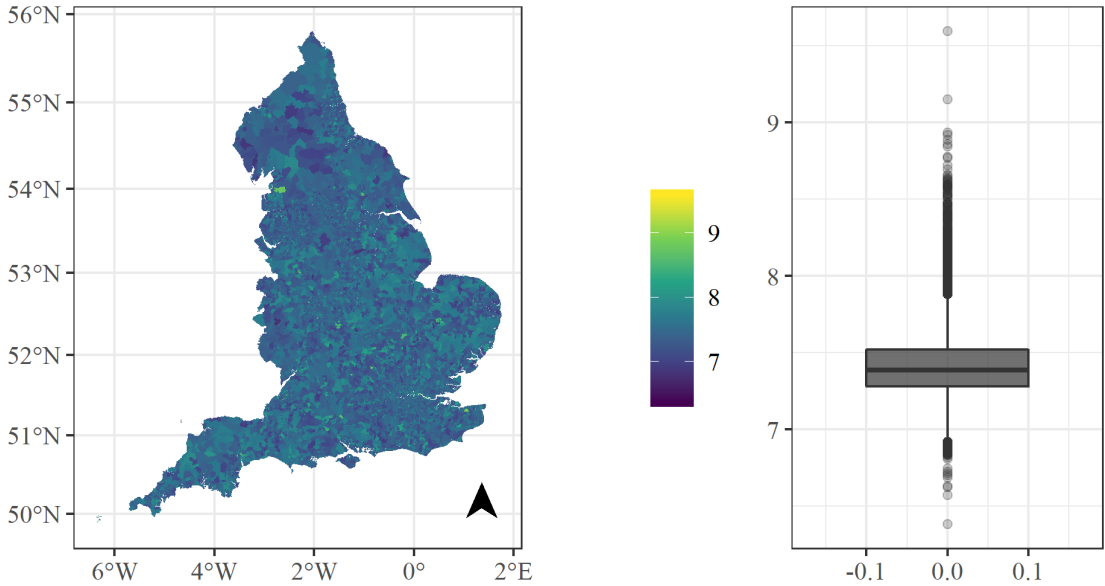


Figure S15: Map and boxplot of the number of **intensive care unit beds per population** and NHS trust as of February 2020.

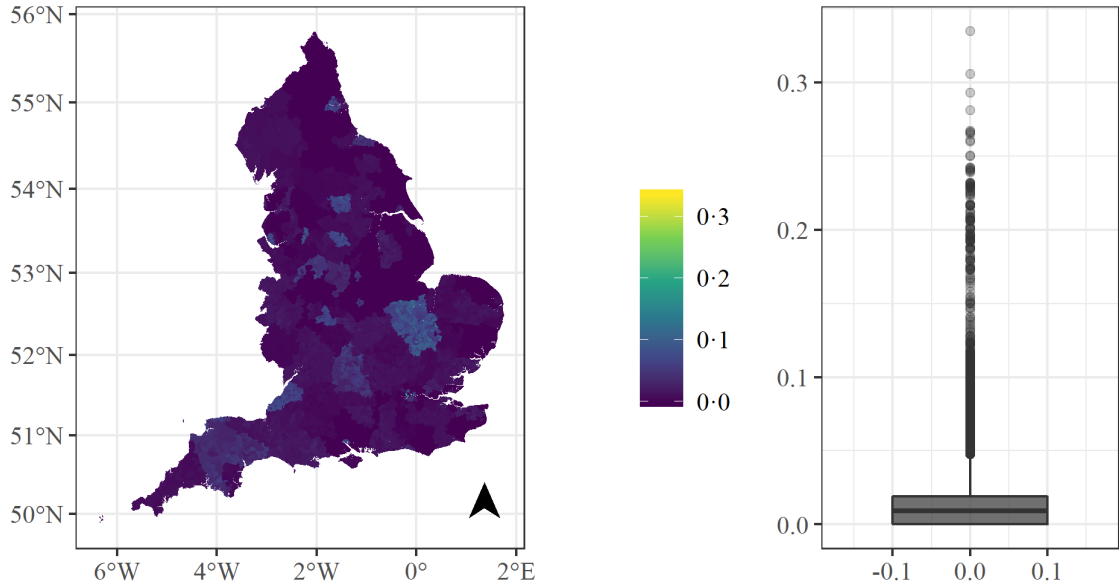


Figure S16: Map and boxplot of the estimated **prevalence of current smokers** in adults (15+) for fiscal year 2018/2019

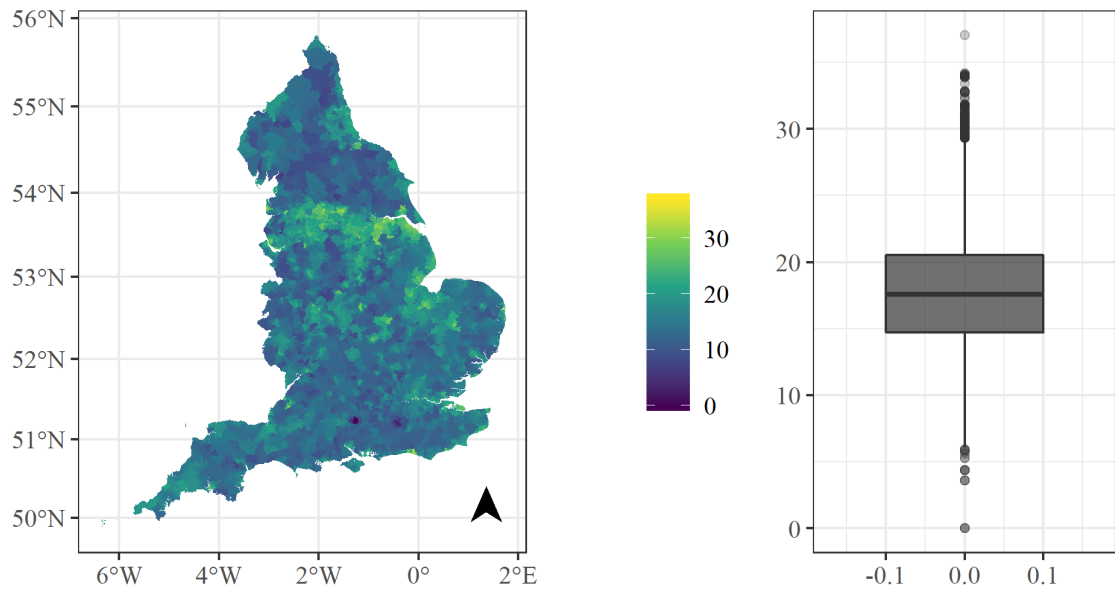


Figure S17: Map and boxplot of the estimated prevalence of obese adults (18+) defined as having a body mass index greater than or equal to 30 in the previous 12 months for fiscal year 2018/2019.

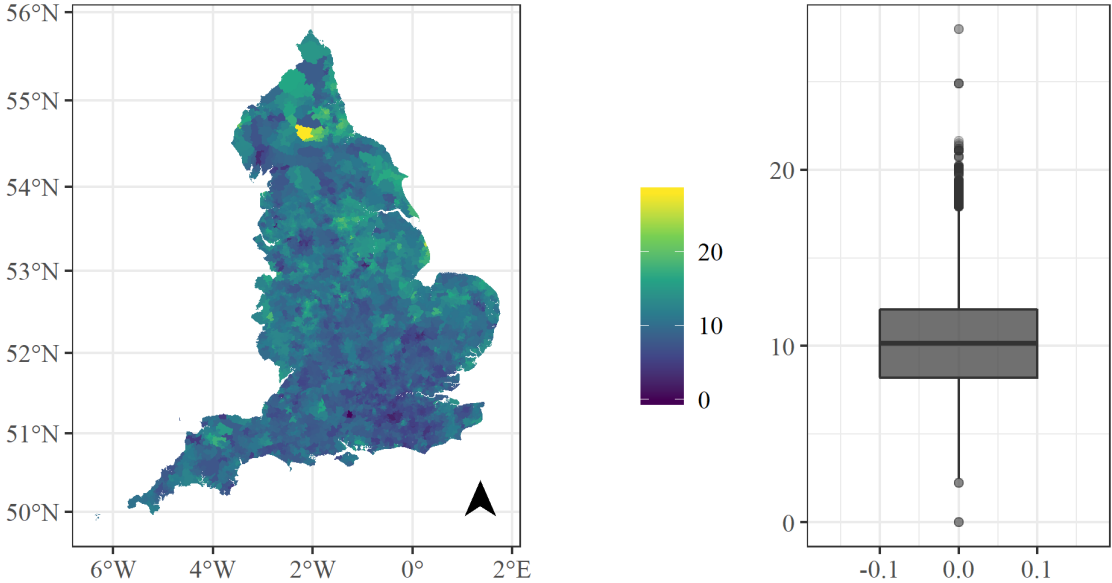
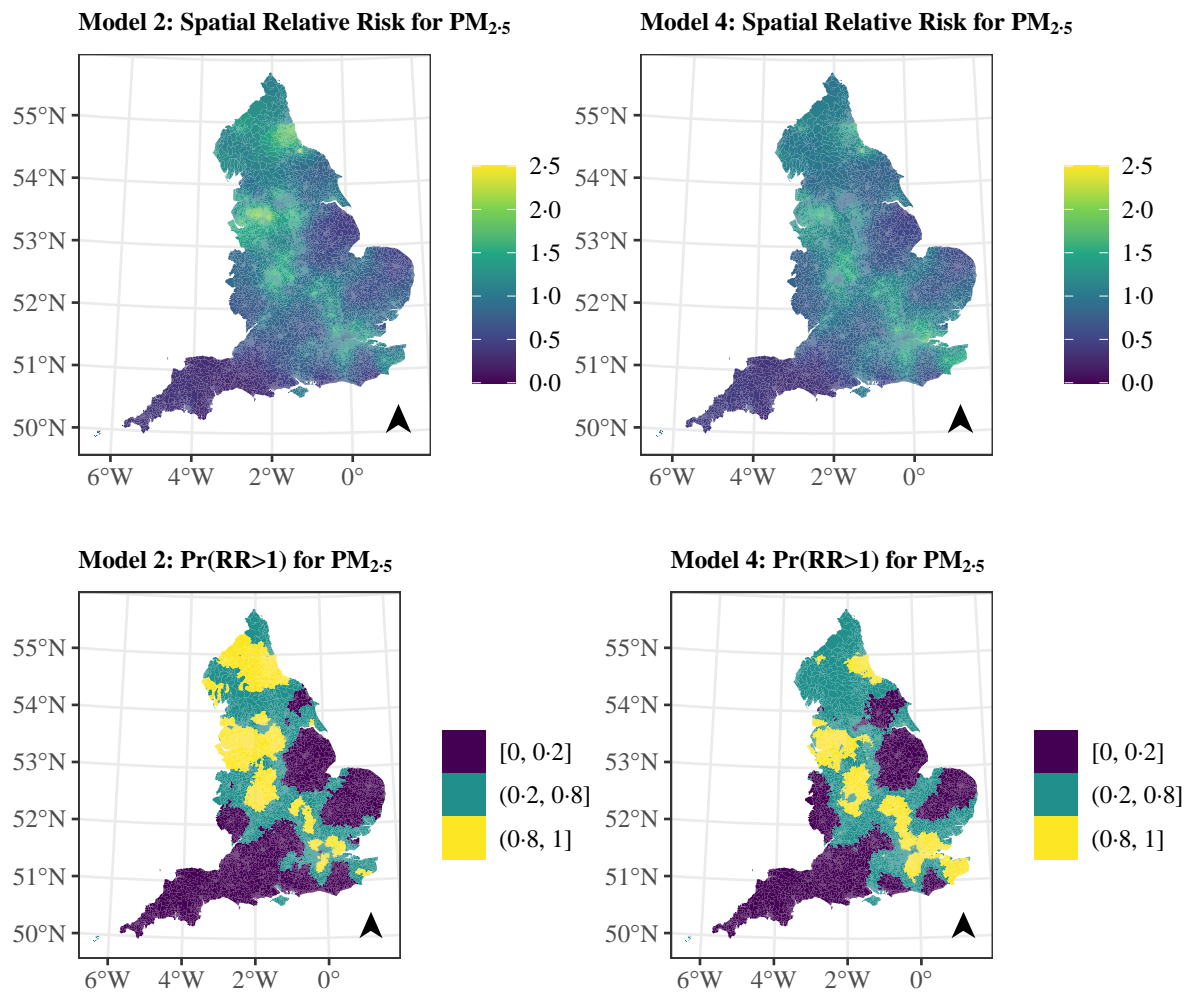


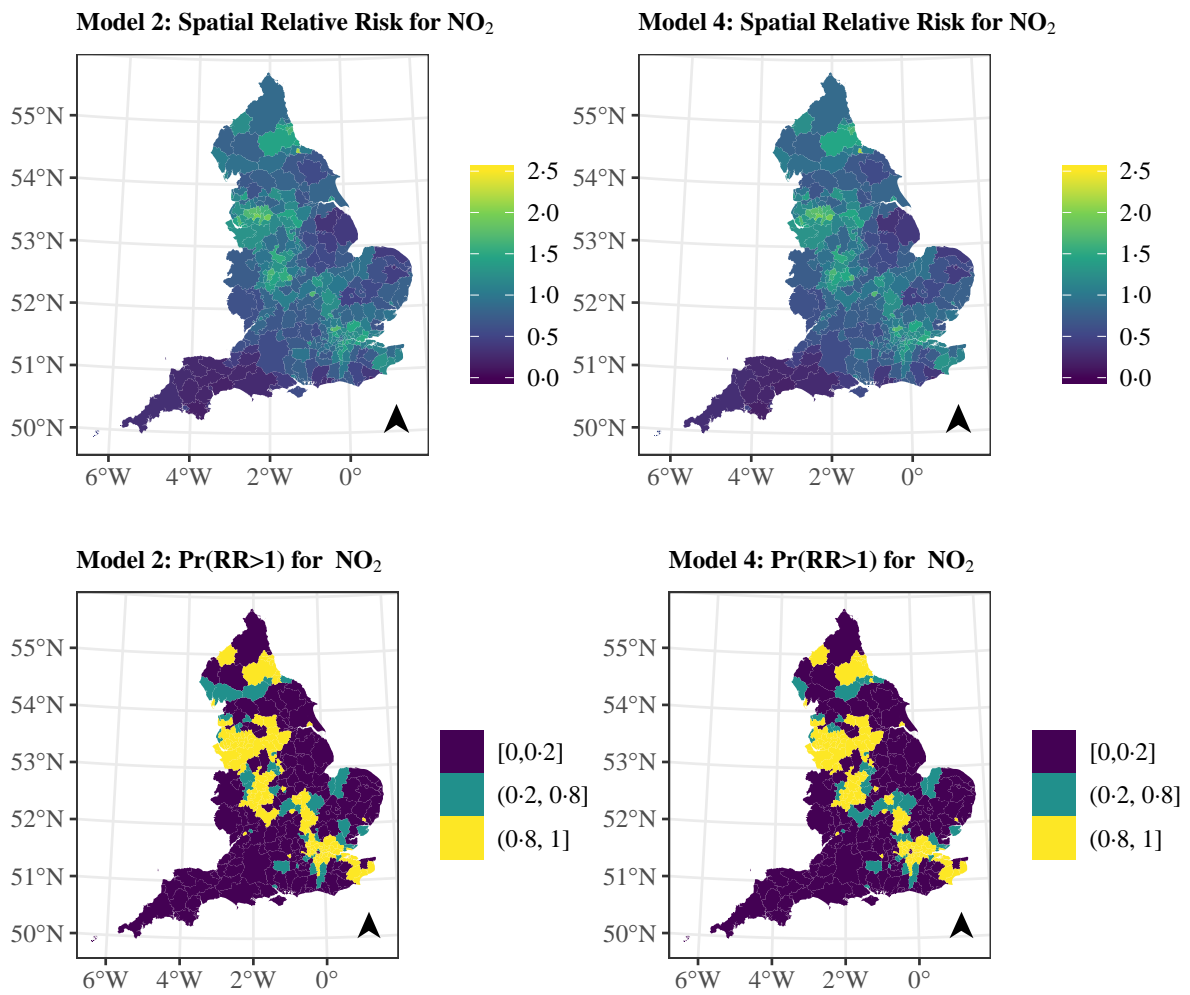
Figure S18: Posterior median **spatial relative risk** (exponential of b) and **posterior probability** that the spatial relative risk is larger than 1 for the models with $PM_{2.5}$ and a spatial autocorrelation term and the fully adjusted $PM_{2.5}$ model at the lower layer super output area level for deaths up to June 30, 2020 (**main analysis**).



Abbreviations: Pr, Probability; RR, spatial relative risk

Model 2: Model with $PM_{2.5}$ and a spatial autocorrelation term, Model 4: Model with $PM_{2.5}$, fully adjusted for confounders and spatial autocorrelation.

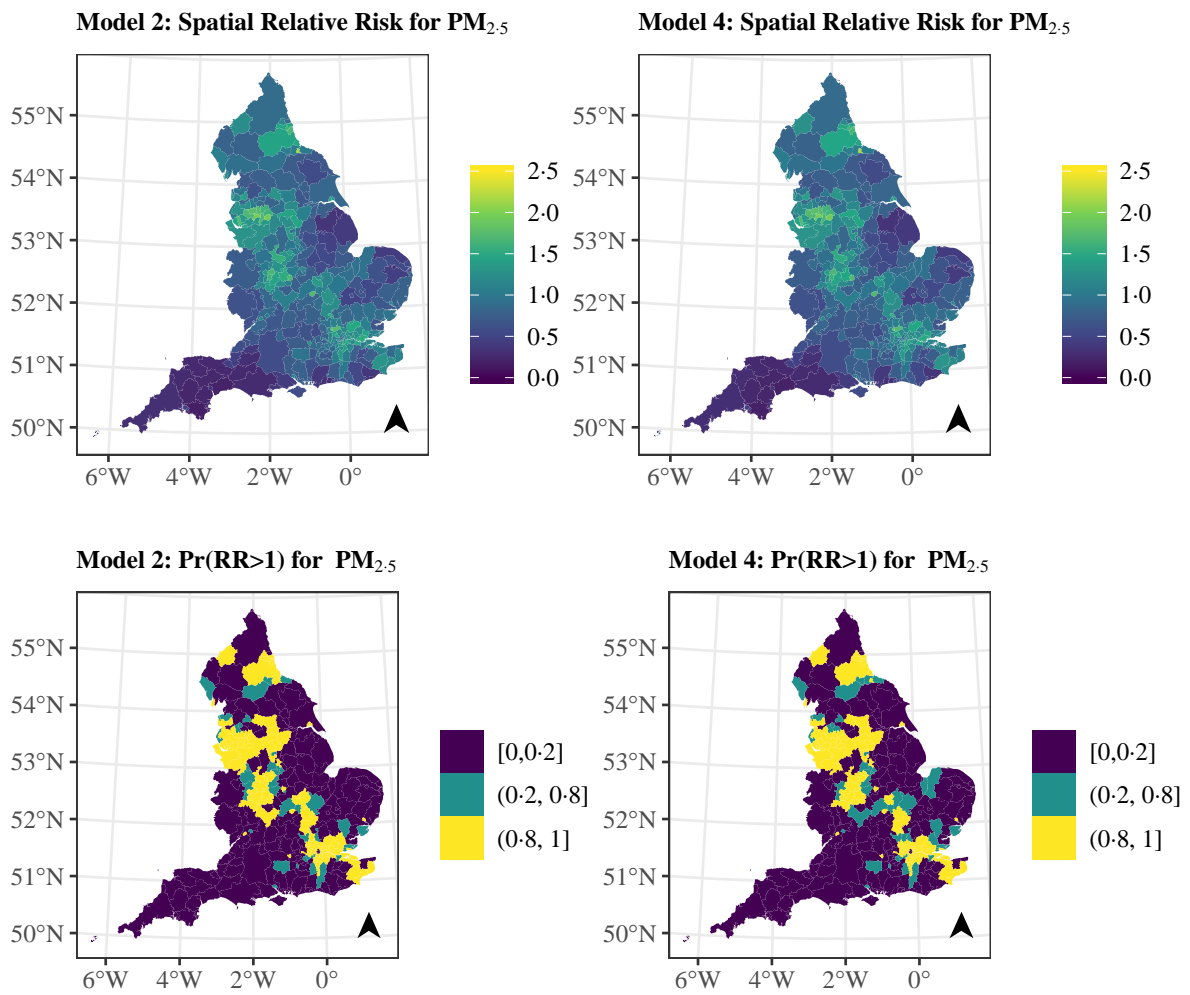
Figure S19: Posterior median **spatial relative risk** (exponential of b) and **posterior probability** that the spatial relative risk is larger than 1 for the models with NO_2 and a spatial autocorrelation term and the fully adjusted NO_2 model fitted at the **lower tier local authority** level for deaths up to June 30, 2020.



Abbreviations: Pr, Probability; RR, spatial relative risk

Model 2: Model with NO_2 and a spatial autocorrelation term, Model 4: Model with NO_2 , fully adjusted for confounders and spatial autocorrelation.

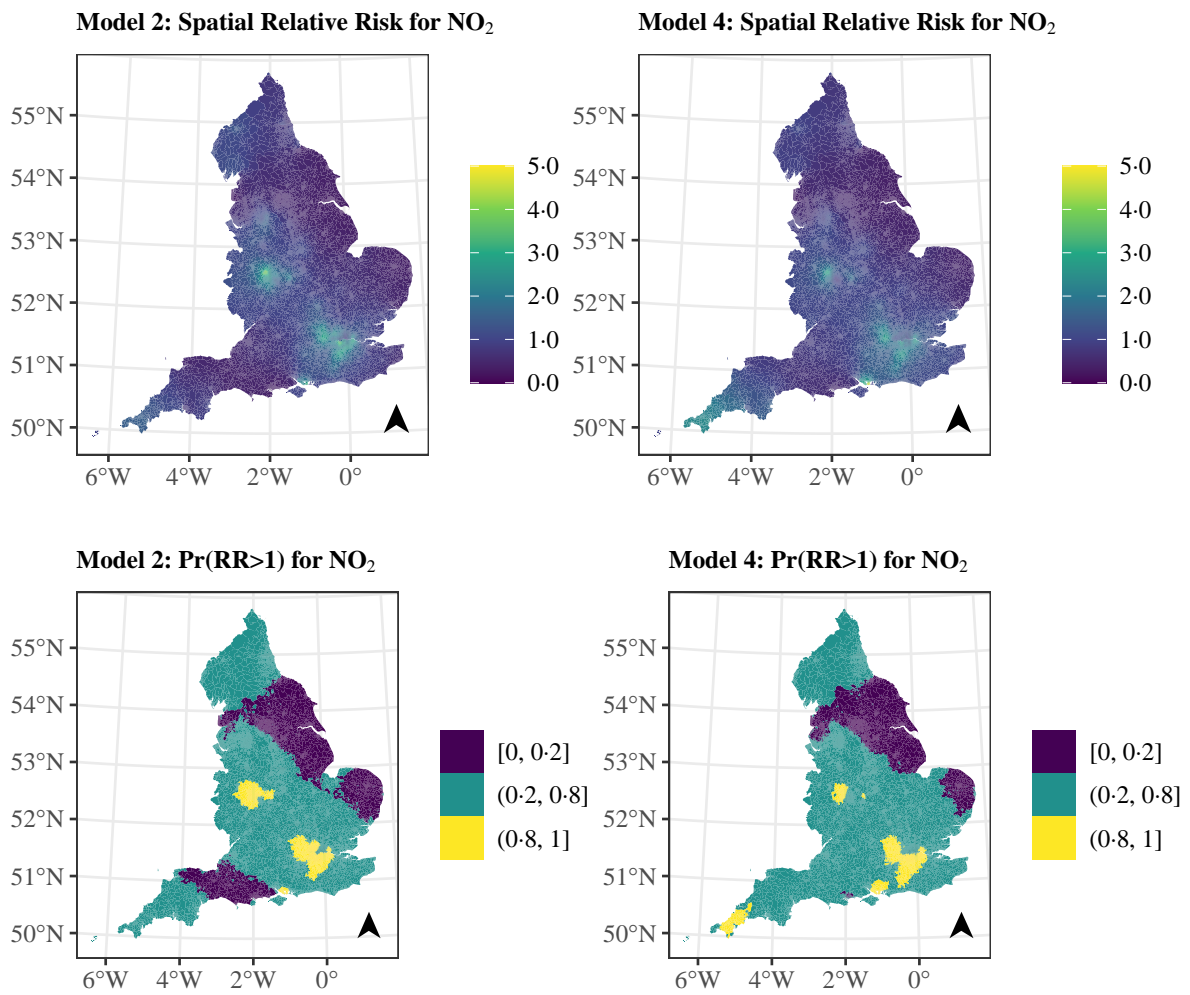
Figure S20: Posterior median **spatial relative risk** (exponential of b) and **posterior probability** that the spatial relative risk is larger than 1 for the models with $PM_{2.5}$ and a spatial autocorrelation term and the fully adjusted $PM_{2.5}$ model fitted at the **lower tier local authority** level for deaths up to June 30, 2020.



Abbreviations: Pr, Probability; RR, spatial relative risk

Model 2: Model with $PM_{2.5}$ and a spatial autocorrelation term, Model 4: Model with $PM_{2.5}$, fully adjusted for confounders and spatial autocorrelation.

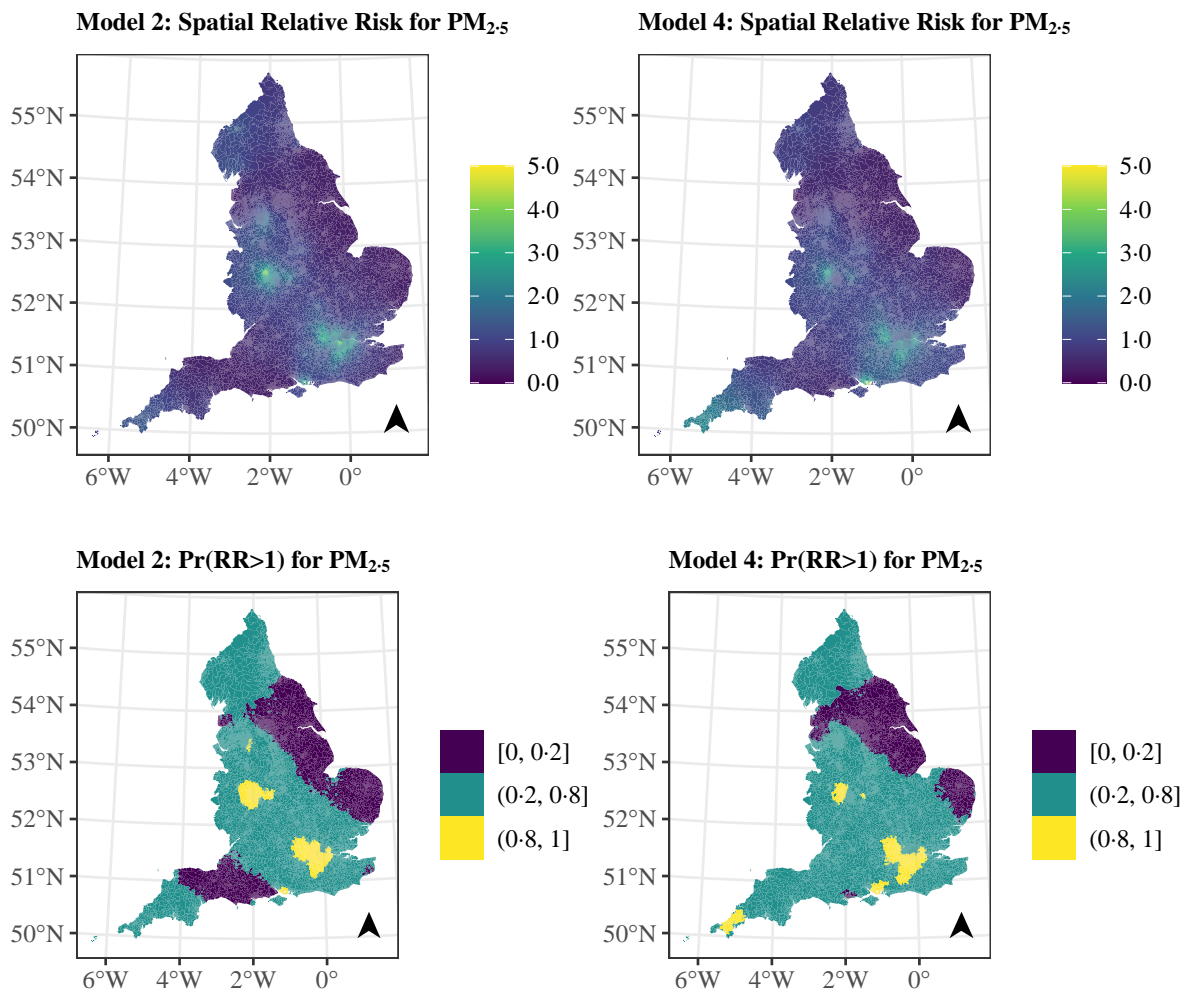
Figure S21: Posterior median **spatial relative risk** (exponential of b) and **posterior probability** that the spatial relative risk is larger than 1 for the models with NO_2 and a spatial autocorrelation term and the fully adjusted NO_2 model for COVID-19 deaths up to March 23, 2020 (**pre-lockdown** period).



Abbreviations: Pr, Probability; RR, spatial relative risk

Model 2: Model with NO_2 and a spatial autocorrelation term, Model 4: Model with NO_2 , fully adjusted for confounders and spatial autocorrelation.

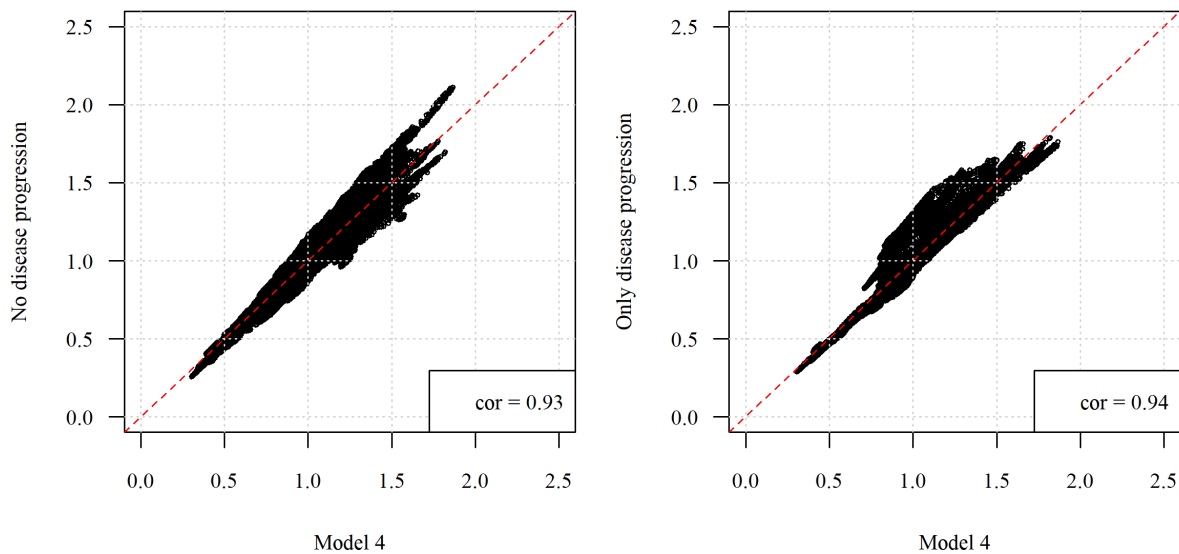
Figure S22: Posterior median **spatial relative risk** (exponential of b) and **posterior probability** that the spatial relative risk is larger than 1 for the models with $PM_{2.5}$ and a spatial autocorrelation term and the fully adjusted $PM_{2.5}$ model for COVID-19 deaths up to March 23, 2020 (**pre-lockdown** period).



Abbreviations: Pr, Probability; RR, spatial relative risk

Model 2: Model with $PM_{2.5}$ and a spatial autocorrelation term, Model 4: Model with $PM_{2.5}$, fully adjusted for confounders and spatial autocorrelation.

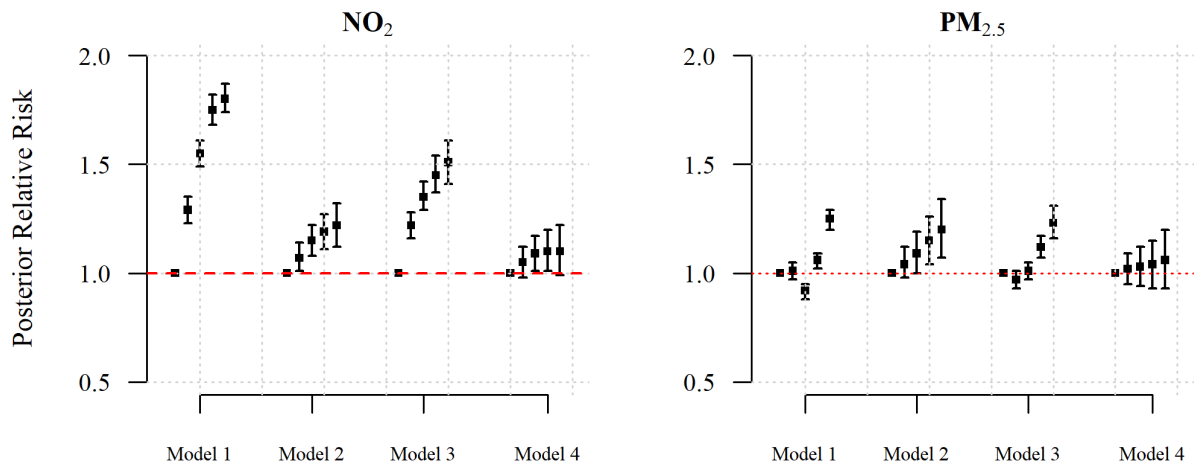
Figure S23: Correlation of the posterior median spatial relative risk for NO₂ (exponential of b) of the model 4 versus the models with and without the covariates associated with disease progression (number of COVID-19 positive cases and days since first reported cases up to June 30, 2020 at the lower layer super output area level).



Abbreviations: cor, correlation coefficient

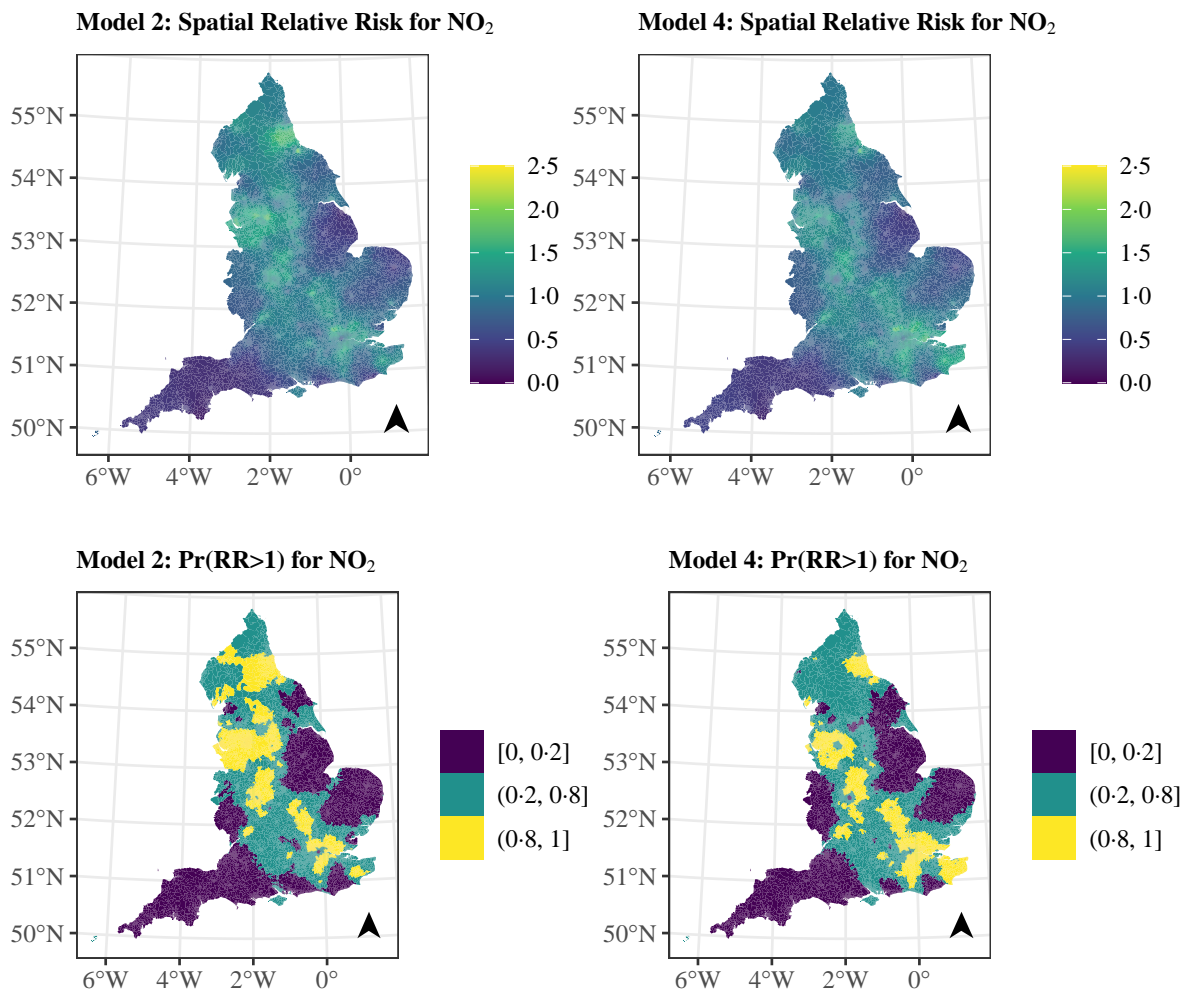
Model 4: Model adjusted for confounding and spatial autocorrelation.

Figure S24: Posterior median together with 95% credibility intervals using the **quintiles** of NO₂ (0%: 2.99, 20%: 10.62, 40%: 13.81, 60%: 16.78, 80%: 20.88, 100%: 50.69) and PM_{2.5} (0%: 5.14, 20%: 8.45, 40%: 9.45, 60%: 10.23, 80%: 11.12, 100%: 14.22) to allow more flexible fits at the lower super output area level for deaths up to June 30, 2020.



Model 1: Unadjusted, model 2: adjusted for spatial autocorrelation, model 3: adjusted for confounding, model 4 adjusted for confounding and spatial autocorrelation.

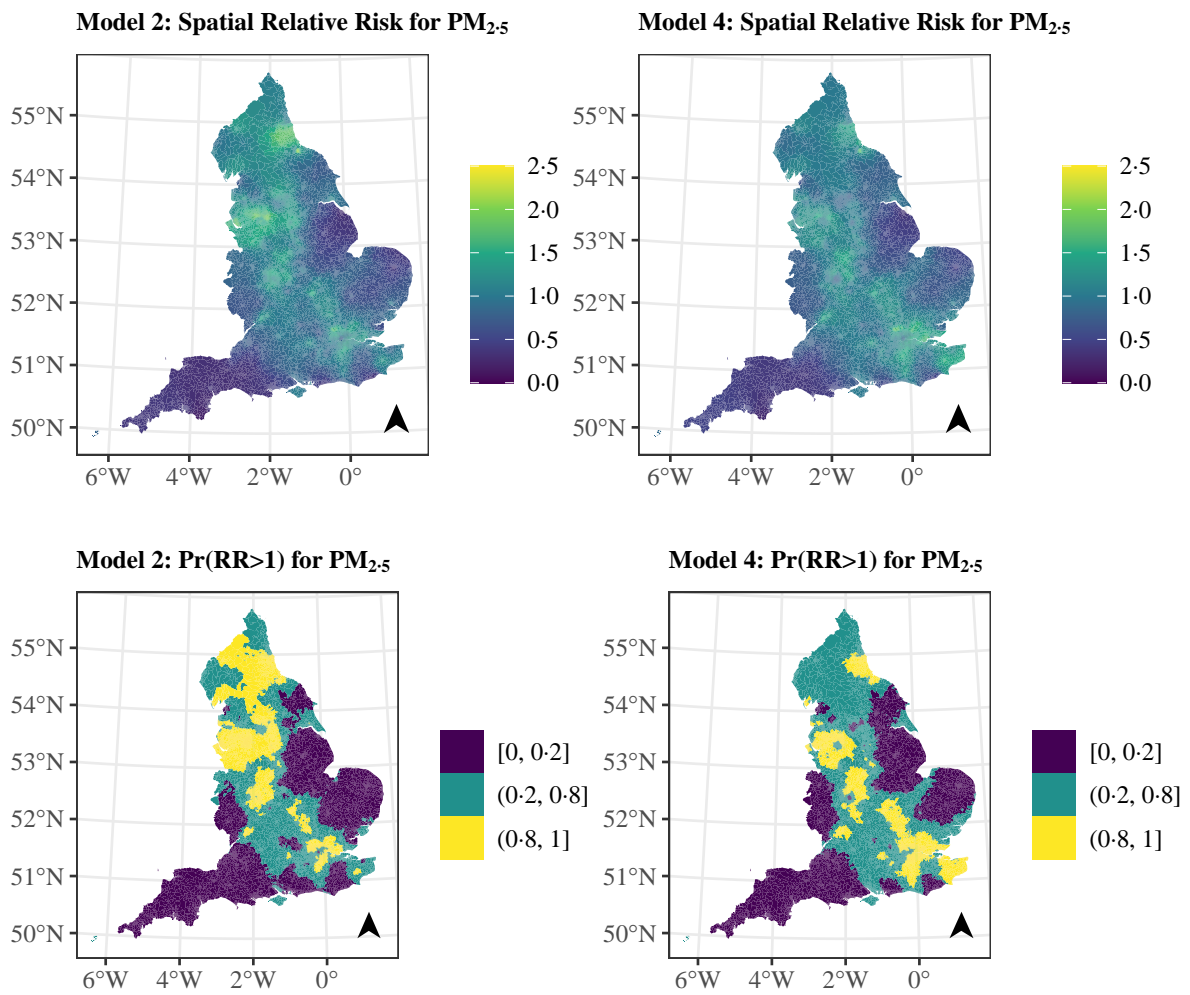
Figure S25: Posterior median **spatial relative risk** (exponential of b) and **posterior probability** that the spatial relative risk is larger than 1 for the models with NO_2 and a spatial autocorrelation term and the fully adjusted NO_2 model for the **suspected COVID-19 deaths** up to June 30, 2020.



Abbreviations: Pr, Probability; RR, spatial relative risk

Model 2: Model with NO_2 and a spatial autocorrelation term, Model 4: Model with NO_2 , fully adjusted for confounders and spatial autocorrelation.

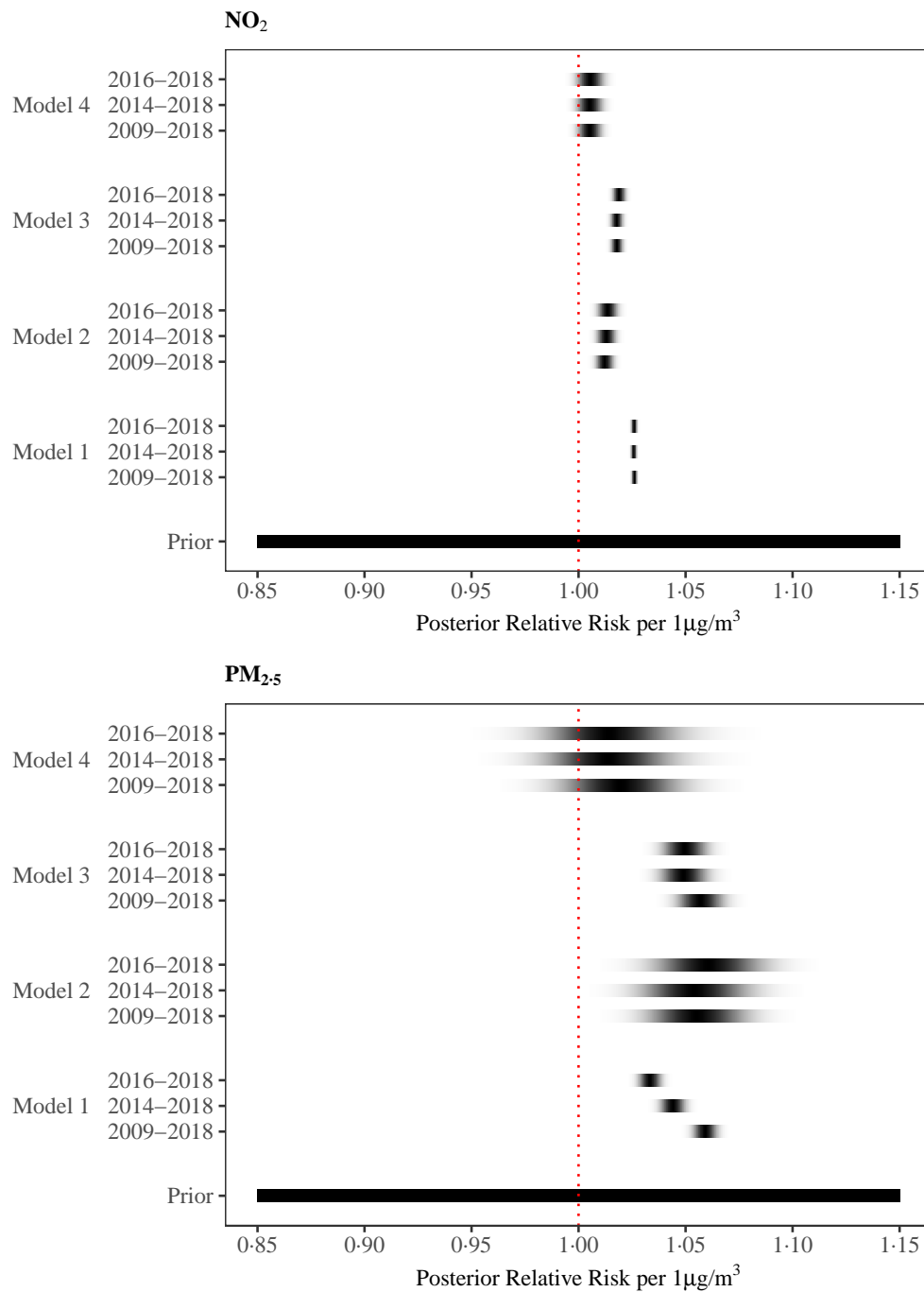
Figure S26: Posterior median **spatial relative risk** (exponential of b) and **posterior probability** that the spatial relative risk is larger than 1 for the models with $PM_{2.5}$ and a spatial autocorrelation term and the fully adjusted $PM_{2.5}$ model for the **suspected** COVID–19 deaths up to June 30.



Abbreviations: Pr, Probability; RR, spatial relative risk

Model 2: Model with $PM_{2.5}$ and a spatial autocorrelation term, Model 4: Model with $PM_{2.5}$, fully adjusted for confounders and spatial autocorrelation.

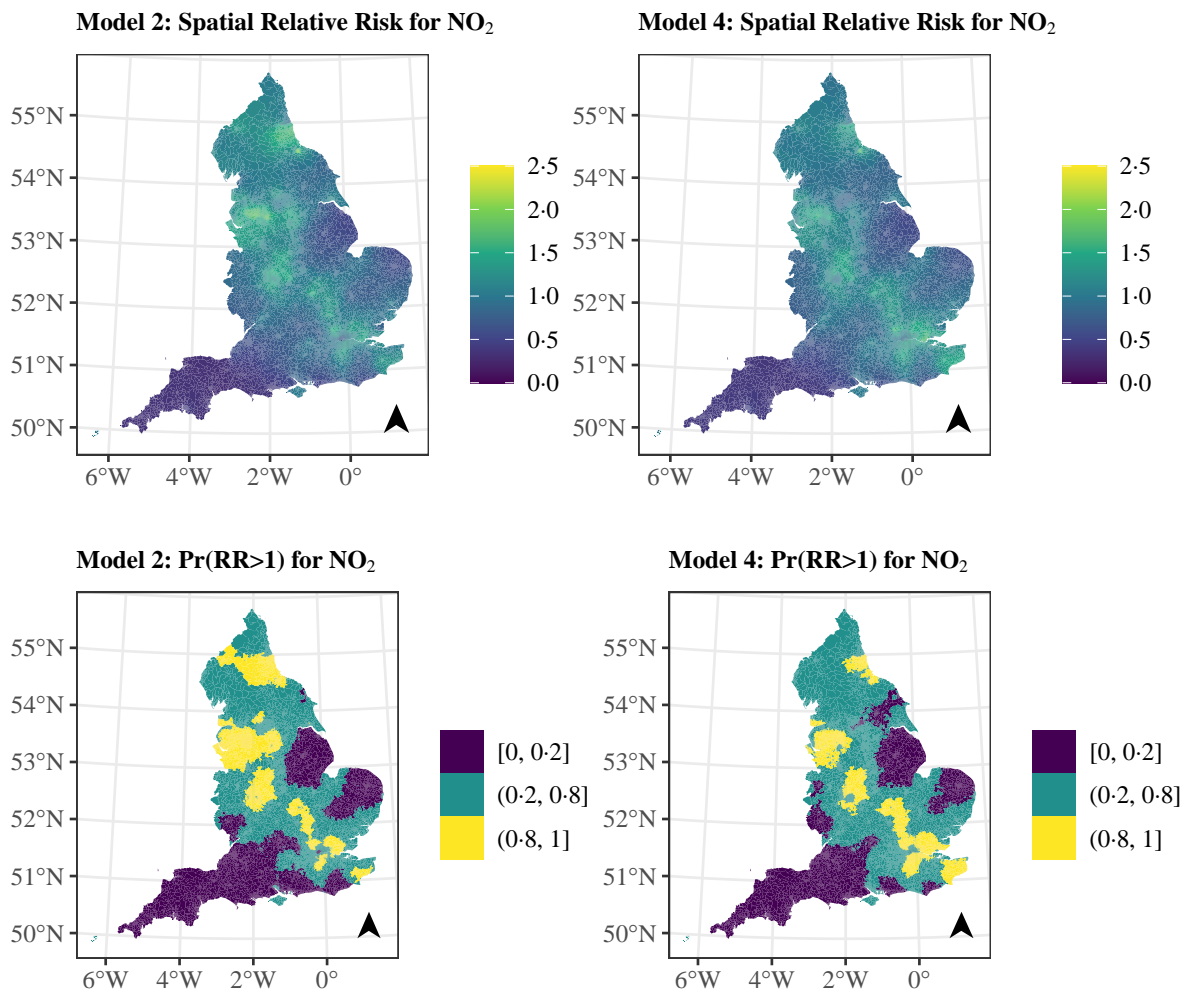
Figure S27: **Density strips** for the posterior of COVID-19 mortality relative risk with $1\mu\text{g}/\text{m}^3$ increase in NO₂ (top panel) and PM_{2.5} (bottom panel) **averaged long-term exposure during 2009-2018, 2014-2018 and 2016-2018**.



Abbreviations: Pr, Probability; RR, spatial relative risk

Model 2: Model with each pollutant, Model 2: Model with each pollutant and a spatial autocorrelation term, Model 2: Model with each pollutant adjusted for temperature, relative humidity, index of multiple deprivation, urbanicity, days since first reported case, number of positive cases, population density number of intensive case unit beds, obesity and high risk occupation, Model 4: Model with each pollutant adjusted for temperature, relative humidity, index of multiple deprivation, urbanicity, days since first reported case, number of positive cases, population density number of intensive case unit beds, obesity, high risk occupation and spatial autocorrelation.

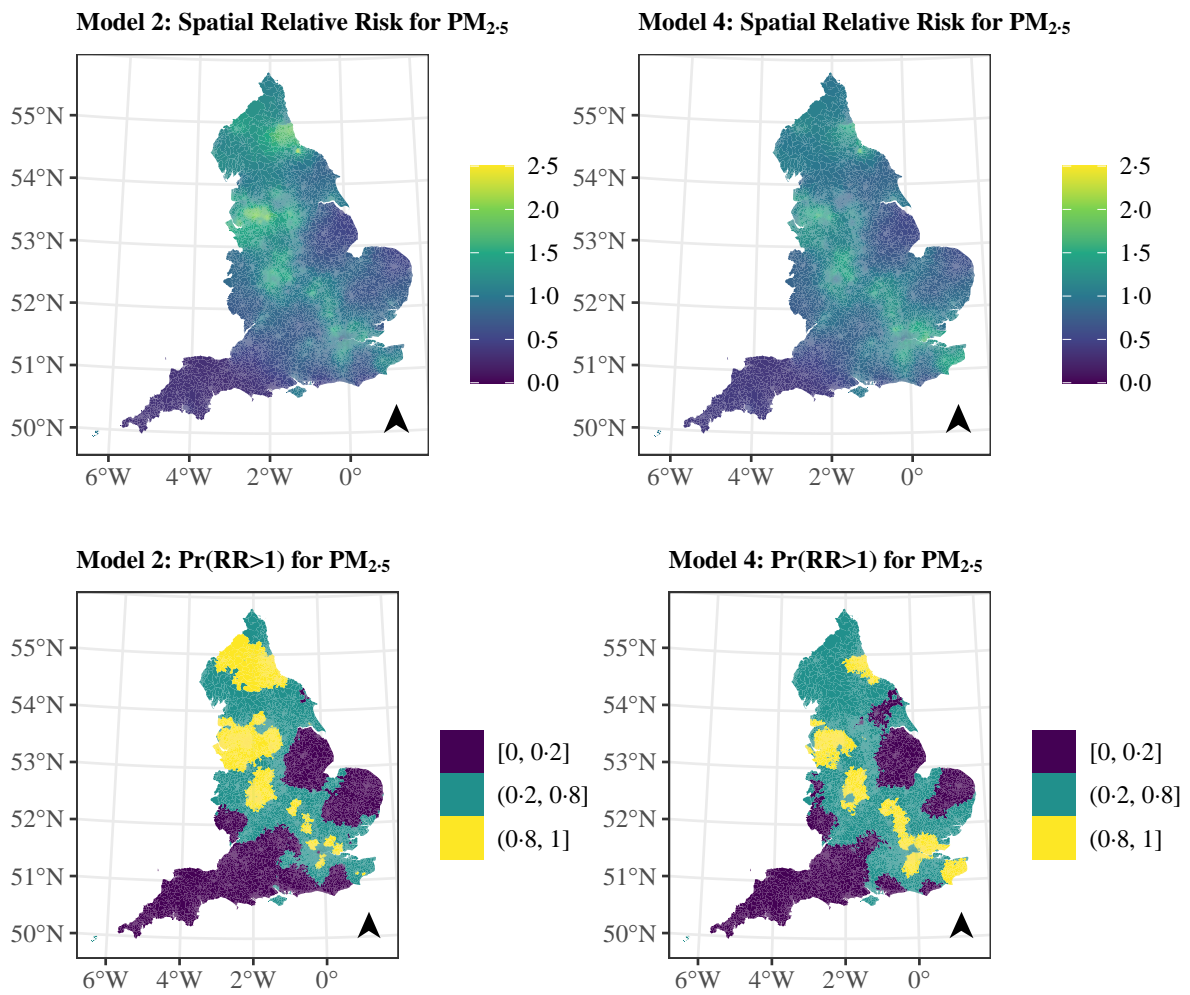
Figure S28: Posterior median **spatial relative risk** (exponential of b) and **posterior probability** that the spatial relative risk is larger than 1 for the **zero-inflated Poisson** models with NO_2 and a spatial autocorrelation term and the fully adjusted NO_2 model for the **confirmed** COVID-19 deaths up to June 30.



Abbreviations: Pr, Probability; RR, spatial relative risk

Model 2: Model with NO_2 and a spatial autocorrelation term, Model 4: Model with NO_2 , fully adjusted for confounders and spatial autocorrelation.

Figure S29: Posterior median **spatial relative risk** (exponential of b) and **posterior probability** that the spatial relative risk is larger than 1 for the **zero-inflated Poisson** models with $PM_{2.5}$ and a spatial autocorrelation term and the fully adjusted $PM_{2.5}$ model for the **confirmed** COVID-19 deaths up to June 30.



Abbreviations: Pr, Probability; RR, spatial relative risk

Model 2: Model with $PM_{2.5}$ and a spatial autocorrelation term, Model 4: Model with $PM_{2.5}$, fully adjusted for confounders and spatial autocorrelation.

Figure S30: Map and boxplot of the estimated prevalence of **hypertension** at the lower layer super output area level for fiscal year 2018/2019.

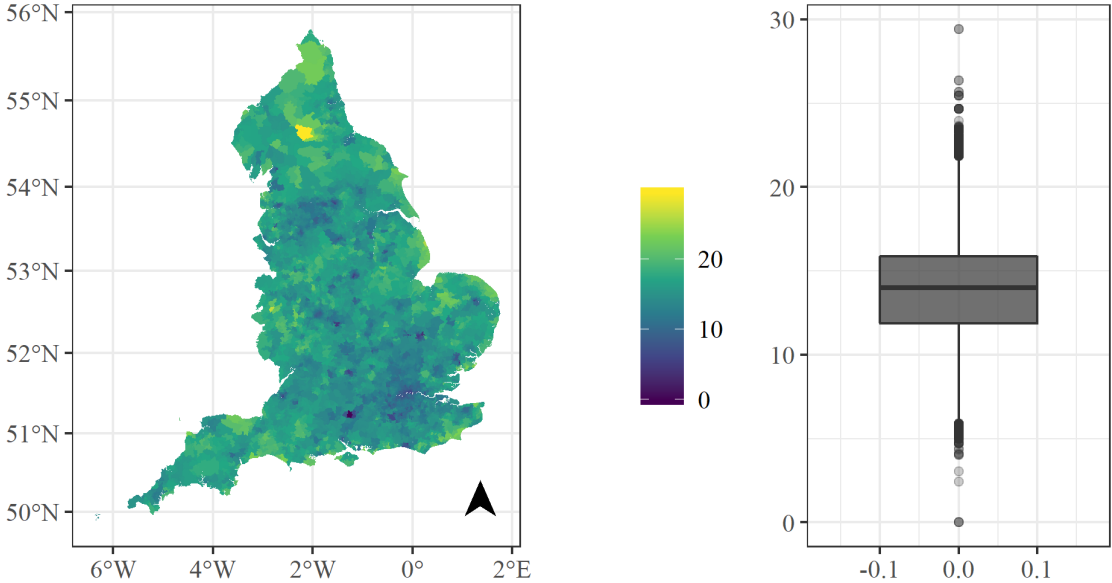


Figure S31: Map and boxplot of the estimated prevalence of **chronic obstructive pulmonary disease** at the lower layer super output area level for fiscal year 2018/2019.

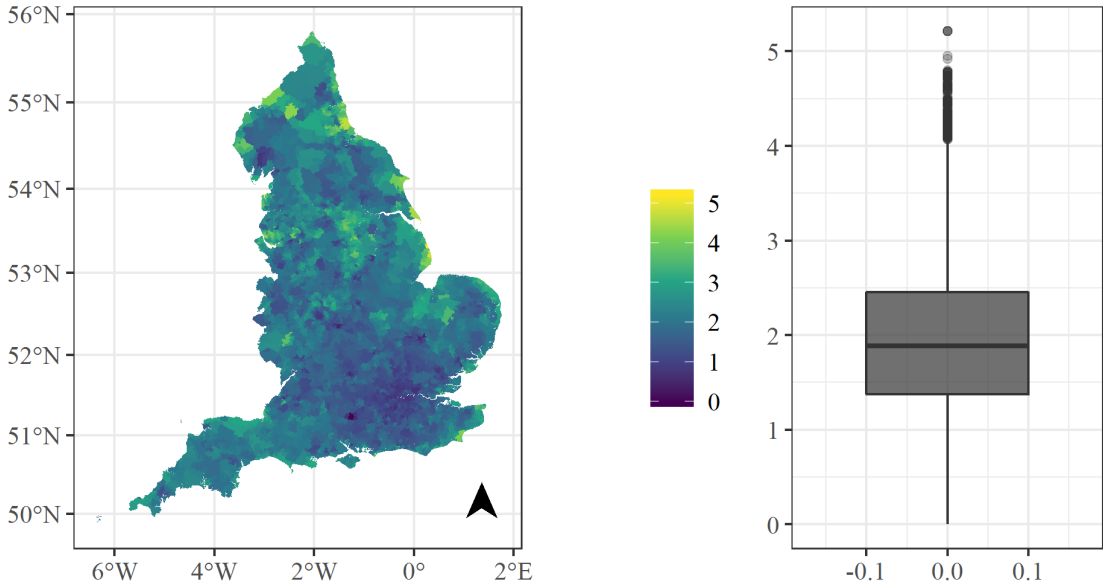


Figure S32: Map and boxplot of the estimated prevalence of **diabetes mellitus** in adults (17+) at the lower layer super output area level for fiscal year 2018/2019.

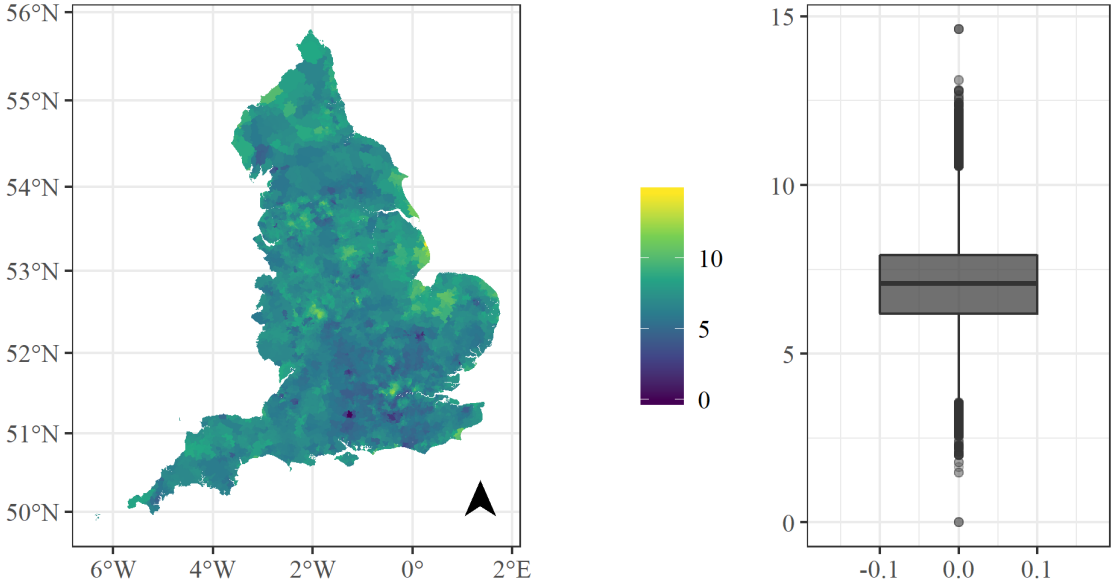
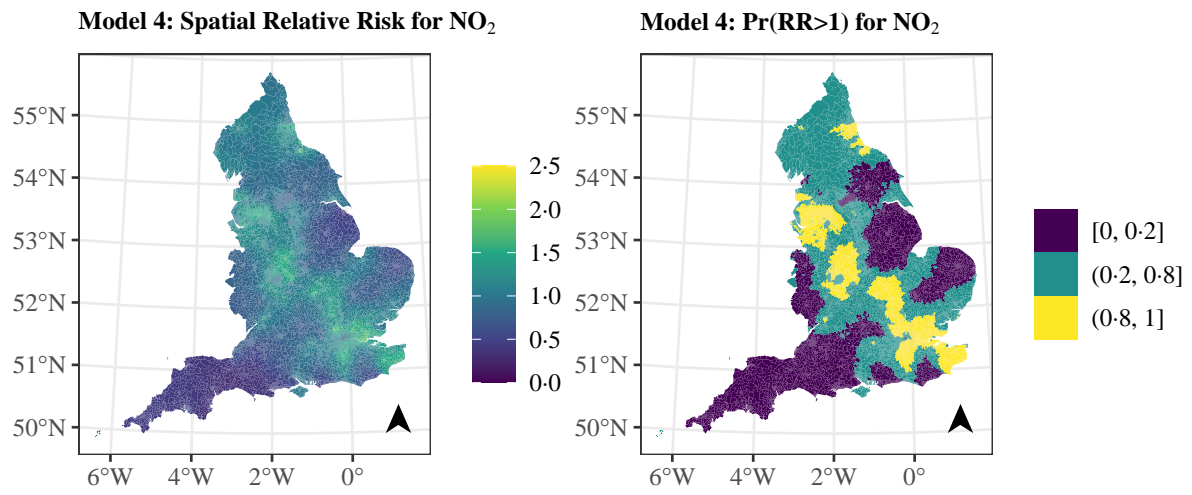


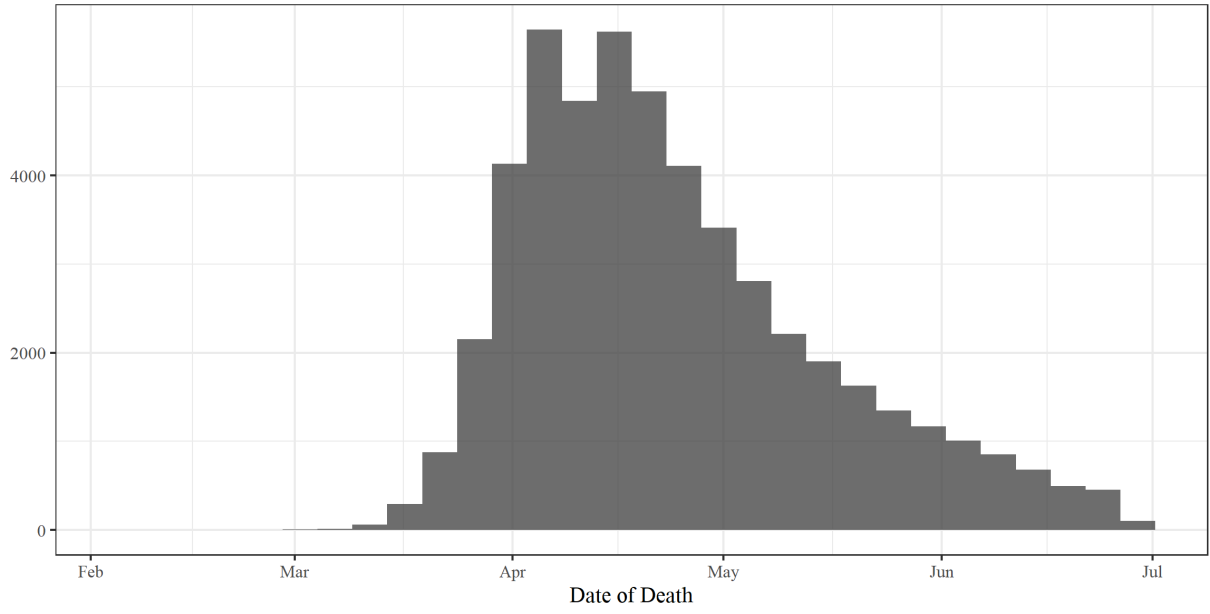
Figure S33: Posterior median **spatial relative risk** (exponential of b) and **posterior probability** that the spatial relative risk is larger than 1 based on model 4 adjusting for area level prevalence of chronic obstructive pulmonary disease, diabetes mellitus and hypertension at the lower layer super output area level for deaths up to June 30, 2020 (**post-hoc analysis**).



Abbreviations: Pr, Probability; RR, spatial relative risk

Model 4: Model with NO₂, fully adjusted for confounders and spatial autocorrelation.

Figure S34: Number of COVID-19 deaths by date of death up to June 30, 2020.



References

- [1] Simpson D, Rue H, Riebler A, Martins TG, Sørbye SH, et al. Penalising model component complexity: A principled, practical approach to constructing priors. *Statistical science*. 2017;32(1):1–28.
- [2] Riebler A, Sørbye SH, Simpson D, Rue H. An intuitive Bayesian spatial model for disease mapping that accounts for scaling. *Statistical methods in medical research*. 2016;25(4):1145–1165.
- [3] Besag J, York J, Mollié A. Bayesian image restoration, with two applications in spatial statistics. *Annals of the institute of statistical mathematics*. 1991;43(1):1–20.