How do socioeconomic deprivation and physical activity levels influence the spatio-temporal patterns of pneumonia mortality across English local authorities between 2002 and 2017?

Abstract

Lower Respiratory Tract Infections (LRTI), including Pneumonia, remain a leading cause of mortality globally and in the UK. In 2024, WHO ranked LRTI as the 5th most common cause of death worldwide (World Health Organization 2024). This dropped to 8th in high income countries, suggesting socioeconomic position may vary risk. Understanding area level risk patterns and the role of deprivation and physical activity may therefore inform public health policy. This report quantified spatiotemporal variation in pneumonia mortality across England's local authorities from 2002 - 2017. A Bayesian spatial BYM2 model identified persistent high risk clusters in London and the North West. The spatio-temporal model highlighted a general decreasing trend in risk over the study period. Including standardised deprivation and physical activity in our spatio-temporal model improved our WAIC from 42885 to 39585 and reduced spatial variability in relative risk estimates. A one standard deviation (SD) increase in deprivation was associated with a 7.7% increase in the relative risk of mortality (RR 1.077, 95% CI 1.058 - 1.097), whilst a one SD increase in physical activity conferred a statistically non significant lower risk (RR 0.997, 95% CI 0.981 - 1.014). Overall we see spatio-temporal clustering of pneumonia mortality, explained in part by deprivation. Therefore, focussing resources on improving deprivation, in the areas identified may lead to improvement in mortality outcomes.

1 Introduction

Pneumonia is a significant cause of mortality worldwide, despite being a preventable and treatable disease. In the United Kingdom, pneumonia causes over 25,000 deaths each year (Asthma and Lung UK 2022). Even with advances in healthcare and vaccination, pneumonia continues to impose a substantial burden on healthcare systems. Although national epidemiological studies have identified key factors associated with pneumonia mortality, such as socioeconomic status, there is a limited understanding of these associations at a local level. Socioeconomic deprivation has been recognised as a key determinant of health outcomes, with pneumonia mortality rates being approximately double in the most deprived communities in England (Office for Health Improvement and Disparities 2021). Lifestyle factors, such as decreased physical activity, have also been proposed as risk factors for pneumonia, with active individuals showing a lower risk of developing severe respiratory infections (Kunutsor, Seidu, and Laukkanen 2022). However, evidence at the local level remains limited. Using Bayesian spatio-temporal analysis, this study addresses the gap by examining geographic variation and temporal trends in pneumonia mortality across 324 English local authorities from 2002 to 2017. We employ the BYM2 spatial model to account for both structured spatial dependence and unstructured heterogeneity in pneumonia mortality patterns. The aim is to quantify local variation and trends in pneumonia mortality, and assess the impact of socioeconomic deprivation and population physical activity. We hypothesise that more deprived areas will show higher pneumonia mortality, while areas with higher physical activity levels may show lower mortality. This study intends to inform targeted public health interventions and improve health outcomes by identifying regions characterised by increased pneumonia mortality and higher deprivation.

2 Methods

This study used a spatio-temporal ecological design to analyse yearly pneumonia deaths across 322 local authorities in England between 2002 and 2017. The outcome of interest was the count of deaths due to pneumonia in each local authority and year. Expected deaths, provided in the dataset, were calculated through indirect standardisation by age and sex using national rates. These expected values were used as an offset to account for differences in population structure. Two area-level covariates were considered as continuous variables: the Index of Multiple Deprivation (IMD) and the percentage of physically active adults, defined as those exercising for more than 30 minutes on more than three days per week. These were obtained from the Fingertips public health data repository. Both were standardised to have a mean of 0 and a standard deviation of 1 for easier interpretation. Geographic boundaries of the local authorities were obtained via shapefiles, and spatial dependence was defined using a queen contiguity structure. This was converted into an adjacency graph suitable for use in the INLA (Integrated Nested Laplace Approximation) modelling framework.

Statistical Modelling

Pneumonia deaths were modelled using a hierarchical Bayesian generalised linear model with a Poisson likelihood and log link function. The logarithm of the expected number of deaths was included as an offset to model standardised mortality ratios (SMRs).

Let y_{it} be the observed number of pneumonia deaths in local authority i at year t, and E_{it} the expected number of deaths. The model is specified as:

$$\begin{aligned} y_{it} &\sim \text{Poisson}(\mu_{it}) \\ \log(\mu_{it}) &= \log(E_{it}) + \eta_{it} \\ \eta_{it} &= \beta_0 + \beta_1 \cdot \text{IMD}_i + \beta_2 \cdot \text{PA}_i + u_i + v_t \end{aligned}$$

μ_{it} is the expected mean number of deaths in local authority i at time t, β_0 is the intercept, β_1 is the regression coefficient for deprivation (IMD), β_2 is the regression coefficient for physical activity (PA), u_i is the spatial random effect, v_t is the temporal random effect.

Spatial Random effects

The spatial random effect u_i was modelled using the BYM2, for flexible modelling of both structured spatial dependence and unstructured heterogeneity:

$$u_i = \frac{1}{\sqrt{\tau_u}} \left(\sqrt{\phi} \cdot s_i^* + \sqrt{1-\phi} \cdot \epsilon_i^* \right)$$

Where s_i^* is the standardised structural spatial effect, ϵ_i^* is the standardised independent and identically distributed (iid) noise, ϕ controls the structured spatial variation, τ_u is the precision.

Temporal Random Effects

Temporal effects v_t were modelled using a first-order random walk (RW1):

$$v_t \mid v_{t-1}, \tau_v \sim \mathcal{N}(v_{t-1}, \tau_v^{-1})$$

With this model, we assume that the risk in each year is similar to the previous one, allowing for a smooth evolution of risk over time, while capturing deviations where supported by the data.

2.0.1 Spatio-Temporal Interaction

To allow each area to have its own temporal trajectory, Type I spatio-temporal interaction term δ_{it} was included. This model assumes an independent and identically distributed (*iid*) structure across space and time, capturing additional unstructured space and time variation. Since Type I interaction makes minimal assumptions about the data while still capturing random variations, it was chosen for the model:

$$\eta_{it} = \beta_0 + \beta_1 \cdot \text{IMD}_i + \beta_2 \cdot \text{PA}_i + u_i + v_t + \delta_{it}$$
$$\delta_{it} \sim \mathcal{N}(0, \tau_\delta^{-1})$$

Interaction was added to the adjusted model, allowing us to assess whether observed spatio-temporal variation could be explained by the covariates. All hyperparameters, including τ_u, τ_v, and ϕ, were assigned penalised complexity (PC) priors, which penalise model complexity in favour of simpler structures unless strongly supported by the data.

3 Results

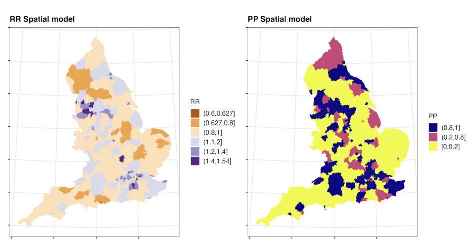
We identified a trend of reduced total deaths from pneumonia between 2002 and 2017. In 2002, the total deaths from pneumonia were 36,730 and in 2017 this number had fallen to 24,800 individuals. We also noted that the trend of expected deaths was inverse to total deaths 1. Furthermore, the Standardized Morbidity Ratio (SMR) across England showed some areas depicting spatial autocorrelation including the local authorities in and surrounding London, as well as those near Liverpool and Manchester. These areas are characterised by higher SMRs, and thus higher rates of pneumonia deaths than expected. Conversely, the North, South West, and East depict lower SMRs.

Grouped Data Summary

period	observed	expected
(2002,2005]	111.19177	80.93227
(2005,2008]	97.97619	85.72438
(2008,2011]	86.21636	91.44759
(2011,2014]	78.36957	99.35388
(2014,2017]	79.34265	105.72491

Figure 1: Figure showing the average observed and expected deaths across all areas for each time period

The baseline spatial models (highlighted in Figure 2), fitted with BYM2, depict the Relative Risks (RRs) and Posterior Probabilities (PPs) after smoothing away random noise. The RRs reinforce the trend observed in our SMRs, evidencing the highest RRs spread across inland areas from London to Manchester and Liverpool. The PPs support the evidence that these cities have the highest relative risks of death by pneumonia. The spatial temporal model depicts a similar pattern of RRs and PPs after accounting for time to the purely spatial model. Moreover, Figure 2 indicates that the spatially structured component in the purely spatial model explains approximately 40% of the spatial variability, supporting the notion of moderate spatial autocorrelation but conversely suggests a large portion of variability is unexplained by the spatially structured component.

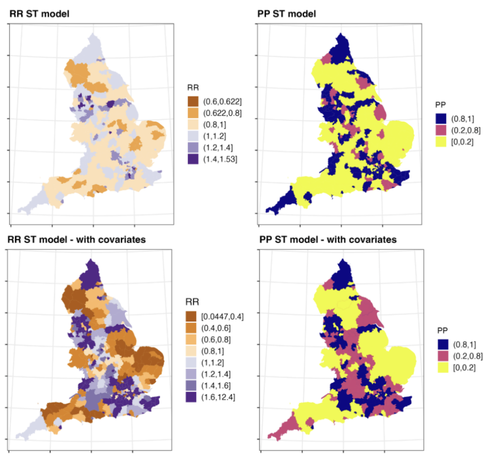


Posterior Summaries of Hyperparameters

Parameter	Posterior Mean	Standard Deviation	Lower 95% CI	Median	Upper 95% CI	Mode
Precision (Spatial)	35.953	3.518	29.495	35.792	43.334	35.494
Phi (Structured Proportion)	0.408	0.091	0.240	0.405	0.595	0.397

Figure 2: Figure highlighting the relative risks and posterior probabilities after smoothing. Note the highest relative risk spread across inland areas from London to Manchester and Liverpool.

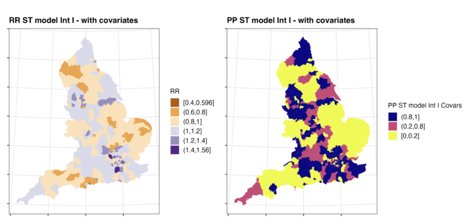
After accounting for deprivation and physical activity (both scaled), but not allowing for area-specific time trends, the RRs show pronounced changes, with lower and higher RRs diverging further. Figure 3, depicts the posterior relative risks for fixed effects and shows an insignificant association between physical activity and pneumonia deaths (as indicated by the credible interval). In contrast, a one standard deviation increase in deprivation is associated with a 7.7% higher rate of pneumonia deaths (95% credible intervals exclude the null).



Covariate	Relative Risk	Lower 95% CI	Upper 95% CI
Intercept	0.974	0.965	0.982
Deprivation (1 SD)	1.077	1.058	1.097
Physical activity (1 SD)	0.997	0.981	1.014

Figure 3: Posterior relative risks of fixed effects and the effect of covariates

Finally, the spatio-temporal models with Type 1 interaction further underpin the spatial and temporal characteristics highlighted thus far. Inclusion of the interaction substantially reduced the maximum estimated relative risk from approximately 12 to 1.5. The high precision values for both the models with and without covariates (34.46, 40.14) indicate low spatial variability. However, the ϕ values for each model indicate strong spatial correlations (76.7%, 85.1%) in the respective models. The precisions for the time components indicate a smooth temporal trend in pneumonia deaths, rather than stark changes between years. This is further reinforced in the Figure 5 (see appendix), depicting the smooth (and declining) temporal residual RRs across the period of study.



Posterior Median and 95% CI of Hyperparameters

	Posterior Median	Lower 95% CI	Upper 95% CI
Precision for ID.space	34.462	26.613	43.453
Phi for ID.space	0.767	0.561	0.911
Precision for ID.time	119.757	54.802	247.781
Precision for ID.space.time	85.537	78.857	92.815

Figure 4: Posterior relative risks and posterior probabilities after adjusting for time and covariates.

The precision for the combined spatial and temporal terms indicates that the changes experienced across the local authorities are more driven by time than differences in space. This notion is further evidenced by the Figure 6 (see appendix) which shows no clear pattern of space-time interaction across the local authorities in the period of study. Lastly, the WAIC values of all the models facilitate model comparison of the spatio-temporal models (as the spatial model is fundamentally different). The WAIC values indicate the best performing model is the spatial temporal model with type 1 space-time interaction and the covariates (WAIC 39585) compared to the spatio-temporal model with no interaction (WAIC 42885). However, the inclusion of the covariates only lowers the WAIC slightly, evidencing their somewhat limited utility. Additionally, a sensitivity analysis was conducted by substituting binary categorical variables in place of the scaled continuous covariates in the spatial temporal model with type 1 interaction. This resulted in a model with higher WAIC scores, indicating worse model fit.

4 Discussion

There are several key findings from this analysis. Firstly, pneumonia deaths have steadily decreased over time, and this trend is largely consistent across local authorities in England. This negative temporal trend is an overall improvement in pneumonia-caused mortality. Secondly, moderate to high levels of spatial structure were observed, with high spatial correlations and a substantive portion of spatial variability (40%) explained by the spatially structured component in the initial spatial model. Furthermore, consistently higher relative risks of death by pneumonia were observed in London and the North West. Inclusion of the time interaction substantially reduced the maximum estimated relative risk. This reduction suggests that much of the extreme spatial risk observed in the simpler model was an artefact of unexplained temporal variation. By modelling time-varying effects, we see more moderate risk estimates and improved model fit, suggesting our model captures different temporal trajectories in each area. Furthermore, the observed spatial autocorrelation implies that local factors beyond deprivation and physical activity might also contribute to pneumonia mortality. To summarise, consistent spatial autocorrelation (and differences) were observed across England, and the changes in these spaces were also consistent over the period of study, decreasing over time. Regarding the inclusion of covariates, deprivation was found to be associated with higher pneumonia mortality rates but not physical activity. The association of deprivation and respiratory diseases, including pneumonia, is also consistent with past literature (Hawker et al. (2003)).

5 Conclusion

Our research has contributed to existing literature by further refining potential areas of focus for understanding spatial temporal differences in pneumonia deaths, principally: 1) temporal trends for pneumonia are observed across space, so by looking into the factors of this decreasing trend would allow us to better approach the challenge of pneumonia (and respiratory deaths) 2) deprivation is a possible factor contributing to consistent differences in pneumonia mortality across space. While highlighting spatial temporal differences of pneumonia deaths in England, the study has several limitations that should be acknowledged. Since ecological study designs are subject to ecological fallacy, effects observed at the group level might not be reflective at the individual level. Future research could investigate spatial temporal trends of deprivation and pneumonia at a more granular geographic scale, whilst also considering further covariates such as environmental factors which may be driving the variation.

6 Supplementary material

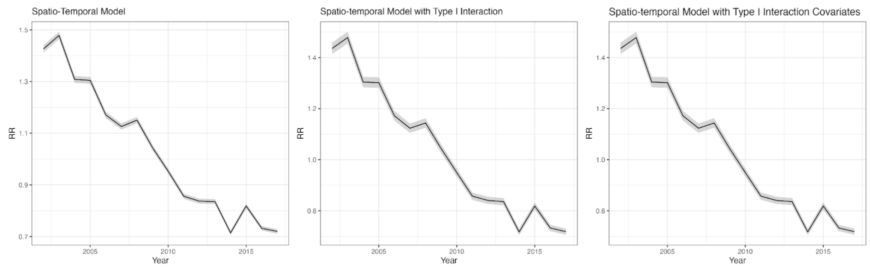


Figure 5: Smooth and declining trend in pneumonia mortality over time

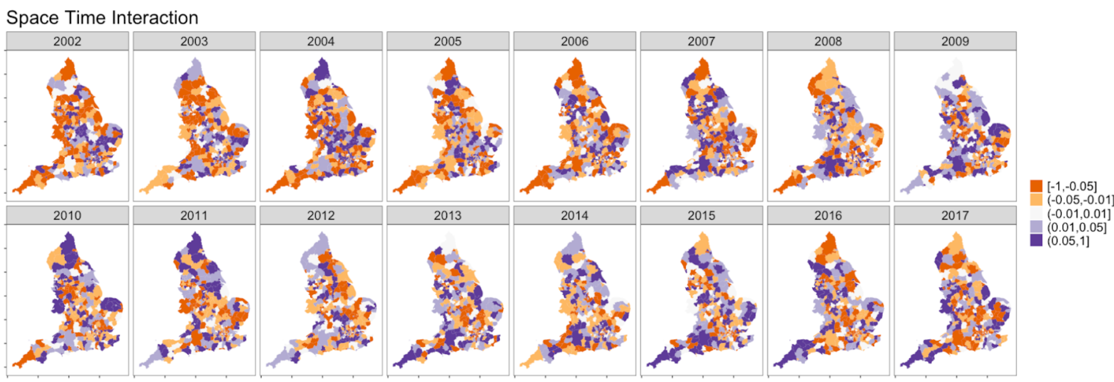


Figure 6: No clear pattern of space-time interaction across local authorities in period of study

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