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Spatial patterns of COVID-19 and non-COVID-19 mortality across waves of infection in England, Wales, and Scotland

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ABSTRACT

Recent studies have established the key individual-level risk factors of COVID-19 mortality such as age, gender, ethnicity, and socio-economic status. However, the spread of infectious diseases is a spatial and temporal process implying that COVID-19 mortality and its determinants may vary sub-nationally and over time. We investigate the spatial patterns of age-standardised death rates due to COVID-19 and their correlates across local authority districts in England, Wales, and Scotland across three waves of infection. Using a Spatial Durbin model, we explore within- and between-country variation and account for spatial dependency. Areas with a higher share of ethnic minorities and higher levels of deprivation had higher rates of COVID-19 mortality. However, the share of ethnic minorities and population density in an area were more important predictors of COVID-19 mortality in earlier waves of the pandemic than in later waves, whereas area-level deprivation has become a more important predictor over time. Second, during the first wave of the pandemic, population density had a significant spillover effect on COVID-19 mortality, indicating that the pandemic spread from big cities to neighbouring areas. Third, after accounting for differences in ethnic composition, deprivation, and population density, initial cross-country differences in COVID-19 mortality almost disappeared. COVID-19 mortality remained higher in Scotland than in England and Wales in the third wave when COVID-19 mortality was relatively low in all three countries. Interpreting these results in the context of higher overall (long-term) non-COVID-19 mortality in Scotland suggests that Scotland may have performed better than expected during the first two waves. Our study highlights that accounting for both spatial and temporal factors is essential for understanding social and demographic risk factors of mortality during pandemics.

1. Introduction

The COVID-19 pandemic has led to further rapid declines in life expectancy in many high-income countries (Schöley et al., 2022). In England and Wales, life expectancy at birth dropped by 0.9 and 1.2 years for women and men, respectively, during the first wave of the pandemic (Aburto et al., 2021). Many studies have investigated the social determinants of COVID-19 mortality, and hence individual-level risk factors for hospitalisation and mortality are well understood. Being older, male, from an ethnic minority background, and having lower socio-economic status are associated with a higher risk of COVID-19 mortality (e.g., Acosta et al., 2021; Bosworth et al., 2021; Brandén et al., 2020; Drefahl et al., 2020; Elliott et al., 2021; Nafilyan et al., 2021). These disparities are driven by individual- and community-level factors, including underlying morbidity and vulnerability to COVID-19, vaccination rates, and the broader social determinants of health (Bambra et al., 2020; McGowan and Bambra, 2022).

The spread of infectious diseases is intrinsically a spatial and temporal process (Breen and Ermisch, 2021). Hence, COVID-19 mortality varies substantially at sub-national scales. This variation is related to a range of compositional factors (e.g., Fielding-Miller et al., 2020; Sartorius et al., 2021; Tchicaya et al., 2021), contextual aspects (e.g., Breen and Ermisch, 2021; Fielding-Miller et al., 2020; Griffith et al., 2021; Harris, 2020; Sun et al., 2021), and health status (e.g., Daras et al., 2021). These intersecting, multi-scalar, biological, social, and environmental factors affect both the likelihood of becoming infected with COVID-19 and its severity. Analysis of these drivers over time and place is essential to understand inequalities related to COVID-19 mortality and how future pandemics could evolve. However, existing ecological studies of COVID-19 mortality have several methodological weaknesses,

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which contribute to mixed and inconclusive findings.

First, as the disease is airborne and transmitted through close contact, it is vital to take into account spatial proximity (Breen and Ermisch, 2021). Many of the broader social determinants of health (e.g., area-level deprivation) proposed to influence COVID-19 mortality also operate at aggregate scales. While previous ecological studies have explored individual and area-level determinants, to our knowledge, only one study has fully accounted for spatial dependency and spillover impacts (Breen and Ermisch, 2021). Second, many ecological studies do not properly account for population age structure, which is a key driver of the severity of infection. The share of the population over 65 is often included in models with crude death rate from COVID-19 or the number of COVID-19 deaths as the outcome variable. Although such an approach may seem justified in the context of limited available information on age-specific mortality, it is too crude to draw conclusions about the determinants of COVID-19 mortality. Third, most studies focus on the first COVID-19 wave, where protection from the virus was achieved through social distancing and lockdowns rather than vaccination. As both the disease and our response to it have evolved, the relative importance of social and demographic factors might also have changed. Fourth, considering both COVID-19 and non-COVID-19 deaths provides a more complete picture of the direct and indirect impacts of the pandemic, but relatively few studies of sub-national COVID-19 mortality do this. Finally, in the context of the UK, which has considerable regional health and social divides alongside nationally devolved health policy, considering both within- and between-country variation is important.

We fill these gaps by investigating the spatial and temporal patterns of age-standardised COVID-19 and non-COVID-19 mortality and factors driving disparities in local authority districts in the three countries of the UK (England, Wales, and Scotland; i.e., Great Britain). We do not analyse Northern Ireland because it is spatially connected to the northern regions of Ireland (i.e., via daily social interaction) rather than the three countries of Great Britain. This suggests that its area-level COVID-19 and non-COVID-19 mortality levels are most likely to be influenced by those in neighbouring areas in Ireland rather than in Great Britain. We show how the Standardised Mortality Ratio (SMR) can be used to investigate changes in spatial patterns of COVID-19 mortality. We use Spatial Durbin models to study both within- and between-country variation in age-adjusted death rates, accounting for spatial dependency and spillover impacts.

2. Background

2.1. Individual-level and ecological studies on COVID-19 mortality

Individual-level studies consistently find that being older, male, from an ethnic minority background, having pre-existing illnesses, living in a multi-generational household, and having lower socio-economic status are associated with a higher risk of COVID-19 mortality. This has been shown in different national contexts, including England and Wales (Bosworth et al., 2021; Elliott et al., 2021; Nafilyan et al., 2021; ONS, 2020; Public Health England, 2020), Sweden (Brandén et al., 2020; Drefahl et al., 2020), Spain (Politi et al., 2021) and the United States (US) (Acosta et al., 2021). Notable exceptions include a lack of sex differences in the UK (Woodward et al., 2021) and no racial/immigrant differences in the US (Yehia et al., 2020) and Sweden (Gustafsson et al., 2021) after adjusting for all other socio-economic and demographic factors. The mechanism behind some of these factors is biological vulnerability, whereas others may be related to higher exposure to the virus (e.g., multi-generational households and occupational factors). However, most are more complex combinations of these (e.g., ethnicity and deprivation), which relate to the broader social determinants of health (Abrams and Szefler, 2020). Whilst many of the demographic and socio-economic factors also predict non-COVID-19 mortality, this is not the case when it comes to ethnicity. Immigrants and individuals from an ethnic minority group usually have lower all-cause mortality but higher COVID-19 mortality (Aldridge et al., 2020; Ayoubkhani et al., 2021; Drefahl et al., 2020; Fabiani et al., 2021; Nafilyan et al., 2021). In most studies, these differences persist even after adjusting for demographic, socio-economic, and geographical differences.

However, population-wide individual-level data on mortality and all other individual characteristics are only available in some countries. Thus, many studies used aggregate-level (ecological) data to understand the predictors of COVID-19 mortality. These studies generally identify the same risk factors (deprivation, ethnicity, age) but also emphasise the importance of space. For example, Griffith et al. (2021) used multi-level Poisson models to analyse COVID-19 mortality (relative to population size) in England. Using data between March and July 2020, they followed a multi-scale approach (Middle Super Output Areas (MSOAs) were nested in Travel to Work Areas, which were nested in Government Office Regions). They showed that spatial inequalities mattered more for COVID-19 than non-COVID-19 mortality, and the importance of geography increased over time, reflecting the spread of the infection. Additionally, more deprived areas had higher COVID-19 mortality than less deprived areas. Similarly, Daras et al. (2021) used Poisson regression to analyse the association between five vulnerability measures and log age-standardised mortality ratio across English MSOAs. Areas with a larger share of individuals with long-term health conditions, more overcrowding, a larger number of care home beds, and a larger share of ethnic minorities had higher COVID-19 mortality.

In the US, Dalsania et al. (2021) used negative binomial regression to study the determinants of county-level COVID-19 mortality between January and October 2020. They showed that counties with a higher proportion of Black individuals had higher COVID-19 death rates. However, after accounting for health status as well as socio-economic, educational, and socio-demographic factors, only the share of individuals without a high school diploma and without internet access had a significant link with COVID-19 death rates. Although these studies have recognised the importance of contextual differences in the predictors of COVID-19 mortality, their analyses have not been adjusted to account for spatial dependency.

2.2. Spatial analysis of COVID-19 mortality

Increasingly, researchers use spatial methods to understand the area-level predictors of COVID-19 mortality. Risk factors identified include a larger share of minority ethnic groups, older and care-home residents, socioeconomic disadvantage, overcrowded housing, and air pollution. In England, Davies et al. (2021) studied the role of community-level characteristics for all cause excess mortality between March–May 2020 using MSOA-level data and Bayesian spatial models. Communities with a high density of care homes and a higher proportion of residents on income support, living in overcrowded homes, and non-white individuals had an increased risk of excess mortality. Adin et al. (2022) found that after accounting for spatial autocorrelation, ethnic segregation, poor air quality, morbidity, and nursing home location were positively associated with COVID-19 excess mortality.

Others have specifically focused on COVID-19 mortality rather than excess mortality. For example, Sartorius et al. (2021) applied Bayesian hierarchical models to assess spatio-temporal variation in COVID-19 deaths across English MSOAs using data from waves 1 and 2. MSOAs with a higher share of elderly and elderly living in deprivation had significantly higher COVID-19 mortality rates. Alongside socio-demographic factors, environmental factors such as poor air quality (Congdon, 2021) and NO_2 levels (Konstantinoudis et al., 2021) were significantly associated with higher COVID-19 mortality. Another English study showed that next to the share of Black and Asian individuals and unemployment rate across English local authority districts having a positive link to COVID-19 mortality, hospital density and relative humidity had a negative relationship with mortality (Sun et al., 2021). Finally, Harris (2020) studied spatial variation in COVID-19 mortality across London. He predicted the difference in the number of COVID-19 deaths across adjacent neighbourhoods using information on the difference in the independent variables between pairs of neighbours. Using negative binomial regressions and controlling for total population, population density, number of care home beds as well as the number of non-COVID deaths per 1000 adults, he found that COVID-19 mortality was higher in areas with a larger share of minority ethnic groups, higher socio-economic disadvantage, larger households, and a smaller share of young people.

Spatial analyses of COVID-19 mortality have also been conducted in other European countries. For example, in France, Tchicaya et al. (2021) investigated disparities in COVID-19 mortality rates across hospital departments in the first two waves. In the first wave, higher COVID-19 mortality rates were associated with a larger share of men, of people aged 60+, higher population density, and higher prevalence of diabetes, whereas in the second wave, only the density of medical personnel mattered. Using Poisson cluster analysis, another French study showed that a higher share of the population living in overcrowded housing and long-term exposure to higher levels of NO_2 explained the spatial distribution of COVID-19-related hospital deaths (Deguen and Kihal-Talantikite, 2021).

In Germany, the number of COVID-19 deaths was significantly and positively associated with early cases from the beginning of the epidemic, average age, population density, and the share of people employed in elderly care. At the same time, a larger share of schoolchildren and children in daycare, as well as a higher physician density, was associated with a lower number of COVID-19 deaths (Ehlert, 2021). Additionally, there was a positive association between the wealth of a district and infection rates during the first wave, whereas richer districts and those with a higher share of university-educated employees had fewer COVID-19 deaths during the second wave (Plumper and Neumayer, 2020).

In the US, Fielding-Miller et al. (2020) used spatial autoregressive models to study the role of poverty, the share of uninsured individuals younger than 65, the share of individuals engaged in farm work, and the percentage of households without a fluent adult English-speaker for COVID-19 mortality across counties. After controlling for total population, population density, and number of days since the first reported case in a county, a higher percentage of farmworkers, a higher share of individuals living in poverty, higher density, larger population, and a higher percentage of residents aged 65+ were all significant predictors of higher number of COVID-19 deaths in a county. Other studies have focused on the role of social vulnerability, showing that it was associated with higher levels of COVID-19 mortality even after controlling for other factors (e.g., Freese et al., 2021; Islam et al., 2021; Karmakar et al., 2021; Neelon et al., 2020).

Finally, some European cross-national evidence is available on the spatial association between socio-demographic variables and COVID-19 deaths. Sannigrahi et al. (2020) identified total population, poverty, and income as the key factors predicting COVID-19 deaths across Europe. Income and total population had a positive relationship with COVID-19 deaths, whereas poverty had a negative relationship, which is likely explained by other compositional factors (e.g., age structure) not accounted for. A study by Konstantinoudis et al. (2022) analysed excess mortality in 2020 using Bayesian spatio-temporal models on a smaller number of countries but at the sub-national level. Excess mortality varied both within and between countries; it was higher among men and had a U-shaped relationship with air temperature.

The existing literature on the spatial and temporal patterning of COVID-19 mortality has several methodological shortcomings, which contribute to mixed and inconclusive findings. The most serious shortcoming is related to the measurement of COVID-19 mortality. Most studies use the number of COVID-19 deaths per 100,000 population in an area as the dependent variable. However, this ignores the age structure inherent to COVID-19 mortality. Hence, some individual factors may correlate with mortality because of their unequal distribution by age (e.g., low education is more common among older than younger cohorts). Additionally, many studies lack a temporal and spatial dimension that takes account of both within- and between-country effects. The only spatial study, to the authors' knowledge, which has analysed age-standardised COVID-19 mortality rates is the study by Breen and Ermisch (2021). They analysed geographical variation in COVID-19 mortality in England between March–July 2020 using spatial autoregressive models. They showed that areas with higher levels of deprivation, higher population density, and a larger share of non-white populations had higher COVID-19 mortality rates.

The main contributions of our study compared to previous research are fourfold. First, we analyse spatial patterns of COVID-19 and non-COVID-19 mortality across three waves of infections. Second, we study cross-national variation within the countries of Great Britain (i.e., England, Wales, and Scotland). We show that the SMR is a very good substitute for the Age Standardised Mortality Rate (ASMR) when data on mortality by age is not available for spatial units. This is our third contribution. Finally, we estimate Spatial Durbin Models, which allow us to account for the impact of spatially lagged (i.e., neighbouring area) dependent (i.e., mortality) and independent variables (e.g., population density) on the mortality level of an area. We show that this approach significantly improves our understanding of how the pandemic has spread across space.

To summarise, we study the spatial and temporal patterns of age-standardised COVID-19 and non-COVID-19 mortality and factors driving disparities in local authority districts in the three countries of Great Britain. We also show how the SMR can be used to investigate changes in spatial patterns of COVID-19 mortality. In the following sections, we outline the data used, the details of variable construction for the analysis and the methodology used, followed by the result on the country level and sub-national level. We conclude the paper with a discussion and conclusions section.

3. Data

For the country-level analysis, we use age-group specific data published by the Office for National Statistics (ONS, 2022b) on the number of deaths where COVID-19 was the underlying or contributory cause as well as all other causes in England and Wales. Equivalent data for Scotland is published by the National Records of Scotland (NRS, 2022a). For the sub-national analysis, we use information on the number of deaths in Local Authority Districts (LADs) in England, Wales (ONS, 2022c), and Scotland (NRS, 2022b). There are 309 LADs in England, 22 in Wales, and 32 in Scotland. We use weekly data from the week ending 3 January 2020 until the week ending 1 April 2022. We have identified three waves of infection based on the number of deaths in Great Britain (Figure A1): wave 1: January–August 2020; wave 2: September 2020–May 2021; and wave 3: June 2021–March 2022. We use data on the LAD level (rather than at the MSOA level) because monthly information at the MSOA level is only available between 1 March and 31 July 2020.

4. Variables

4.1. Dependent variable

Ideally, to study spatial variation in COVID-19 and non-COVID-19 mortality, we would use LAD-level information on deaths by age and sex. This would allow us to calculate the ASMR, which is the number of deaths per 100,000 individuals expected in a reference population when the observed age-specific mortality rates are applied to the reference population. However, weekly data on deaths by age and sex at the LAD level is only available between March 2020–April 2021 in England and Wales. Thus, we would not be able to cover the entire period between January 2020 and March 2022 and, most importantly, distinguish between the three waves. To overcome this issue, we propose to calculate the SMR. The SMR is calculated by dividing the number of observed deaths in a LAD by the expected number of deaths in that LAD in time period t if the LAD's population experienced the same age-specific mortality rates by sex during the time period as Great Britain as a whole. The mortality rate for age group a and sex s ($M_{a,s,t}$) in period t (e.g., waves) is calculated as:

$$M_{a,s,t} = \frac{D_{a,s,t}}{P_{a,s,t}}$$

where $D_{a,s,t}$ is the number of deaths in Great Britain of those aged a and of sex s in period t and $P_{a,s,t}$ is the population of those aged a and of sex s at the beginning (or in the mid-point) of period t in Great Britain. The SMR for local authority i in period t is then calculated as:

$$SMR_{i,t} = \frac{D_{i,t}}{\sum_{a,s,t} M_{a,s,t} * P_{a,s,i,t}}$$

where $D_{i,t}$ is the observed number of deaths in the local authority in period t and $P_{a,s,i,t}$ is the population of those aged a of sex s in local authority i during period t. The calculation of the SMR (or indirect standardisation) requires less information than that of the ASMR (or direct standardisation). For the former, we need information on the total number of deaths in the local authority, its age structure by sex, and age-specific mortality by sex for Great Britain. These data are available every week from January 2020–March 2022, allowing us to study COVID-19 mortality across different waves of infection.

Some studies suggest that whilst measures calculated using indirect standardisation may show smaller standard errors than those produced using direct standardisation, they may be biased due to potential differences in population structures (Julious et al., 2001). To assess the suitability of using SMR, we have compared the results using ASMR and SMR in England, Wales, and Scotland for the period March 2020–March 2022. The SMR and ASMR are very similar at the LAD level (Figure A2). When regressing ASMR on SMR for both COVID-19 and non-COVID-19 mortality, the Multiple R-squared values are >0.99, suggesting that the SMR is an excellent substitute for ASMR.

4.2. Independent variables

All independent variables are measured at the LAD level. We measure socio-economic status using the index of multiple deprivation (IMD), a composite measure which combines seven domains of deprivation such as income, employment, education, health deprivation and disability, crime, housing, and living environment. Higher values indicate more deprivation. Data on IMD comes from the Ministry of Housing, Communities & Local Government (2019) for England. For Scotland and Wales, we follow the openSIMD project (TheDataLabScotland, 2017) and the method suggested by Abel et al. (2016) to calculate equivalent measures of IMD using data published by the Scottish Government, 2020 and Welsh Government, (2019).

Population data are mid-year estimates by single year of age by LAD for 2020 (ONS, 2021), the latest year for which it is available. Population density in each LAD is calculated by dividing the number of individuals in an area by the size of the area (km^2). We use the natural logarithm of population density to reduce the impact of outliers (e.g., larger urban areas). To measure the influence of ethnic composition, we calculate the share of individuals who belong to an ethnic minority (i.e., who identify as other than 'White British') in each LAD using data from the Annual Population Survey (ONS, 2022a). We calculate the average over 2019, 2020, and 2021 to smooth any variability in the data that may stem from the nature of survey data. To adjust for differences across and to compare mortality in the three countries of Great Britain, we also control for country (England (reference), Wales, and Scotland).

5. Methods

To assess the suitability of OLS models, we calculated Moran's I statistics (Table A1). For both COVID-19 and non-COVID-19 mortality, there is significant spatial autocorrelation in the residuals of OLS models across all waves, suggesting that OLS regression is not appropriate to model COVID-19 and non-COVID-19 mortality. Instead, we use spatial regression models that account for the spatial dependency between the residuals. A range of spatial models has been developed, with spatial lag and error models being the most widely used (Elhorst, 2010; Golgher and Voss, 2016). We estimate a Spatial Durbin model because it is not only able to account for spatial dependencies but also considers so-called spillover impacts, allowing us to investigate how the pandemic has spread across space. The model includes both a spatially lagged dependent variable and spatially lagged explanatory variables and has two advantages over conventional spatial models. First, unlike the spatial error model, the Spatial Durbin model allows us to separate the direct (within a region) impact of an independent variable on the dependent variable from the indirect (to/from adjacent regions) impact. Second, unlike in spatial lag models where the assumption is that each explanatory variable shares the ratio between own-area and lagged relationships, the Spatial Durbin model allows flexibility in these ratios and provides unbiased coefficient estimates, regardless of the true spatial processes underlying the observed data (Elhorst, 2010; Golgher and Voss, 2016; LeSage, 2014). Table A2 shows that the spatial lag model produces some significant indirect impacts not found using the Spatial Durbin model. The Spatial Durbin model is specified as:

$$y = \rho Wy + X\beta + WX\beta_2 + \varepsilon$$

where ρ is the spatial lag coefficient, which captures the relationship between the values of the dependent variable in the neighbouring regions, W is the neighbourhood matrix, which defines the neighbourhood of an area using the inverse weighted distance of an area from its five nearest neighbours, X is the matrix of explanatory variables, and WX is the matrix of spatially lagged explanatory variables (i.e., a linear combination of the variables of the neighbouring areas). The $WX\beta_2$ term indicates the lagged relationships of the explanatory variables in the neighbouring regions.

To interpret the results, we follow LeSage and Pace (2014) and use the matrix of partial derivatives of the data-generating process associated with each variable r:

$$\frac{\partial y}{dx^r} = (I_n - \rho W)^{-1} \left(I_n \beta_{1_r} + W\beta_{2_r}\right)$$

The mean of the main diagonal elements of this matrix relates to the direct marginal impact of a variable. In other words, the direct impact shows how a change in a variable r in an area is related to a change in the dependent variable in that same area (own area impact). The mean of the off-diagonal elements shows the indirect marginal impact of a variable, i.e., the impact of a change in variable r in an area i on a change in the dependent variables of other areas (spillover). The total marginal impact is simply the sum of direct and indirect impacts.

First, we show country-level descriptive results of COVID-19 and non-COVID-19 mortality across the three waves of infection. Then, we describe spatial patterns of COVID-19 and non-COVID mortality across LADs. Finally, we estimate Spatial Durbin models to analyse factors associated with COVID-19 and non-COVID-19 mortality.

6. Results

6.1. Country level

Fig. 1 shows the weekly number of COVID-19 and non-COVID-19 deaths by country (England, Scotland, and Wales) and place of death (home/other, hospital, or care home) during the study period. There

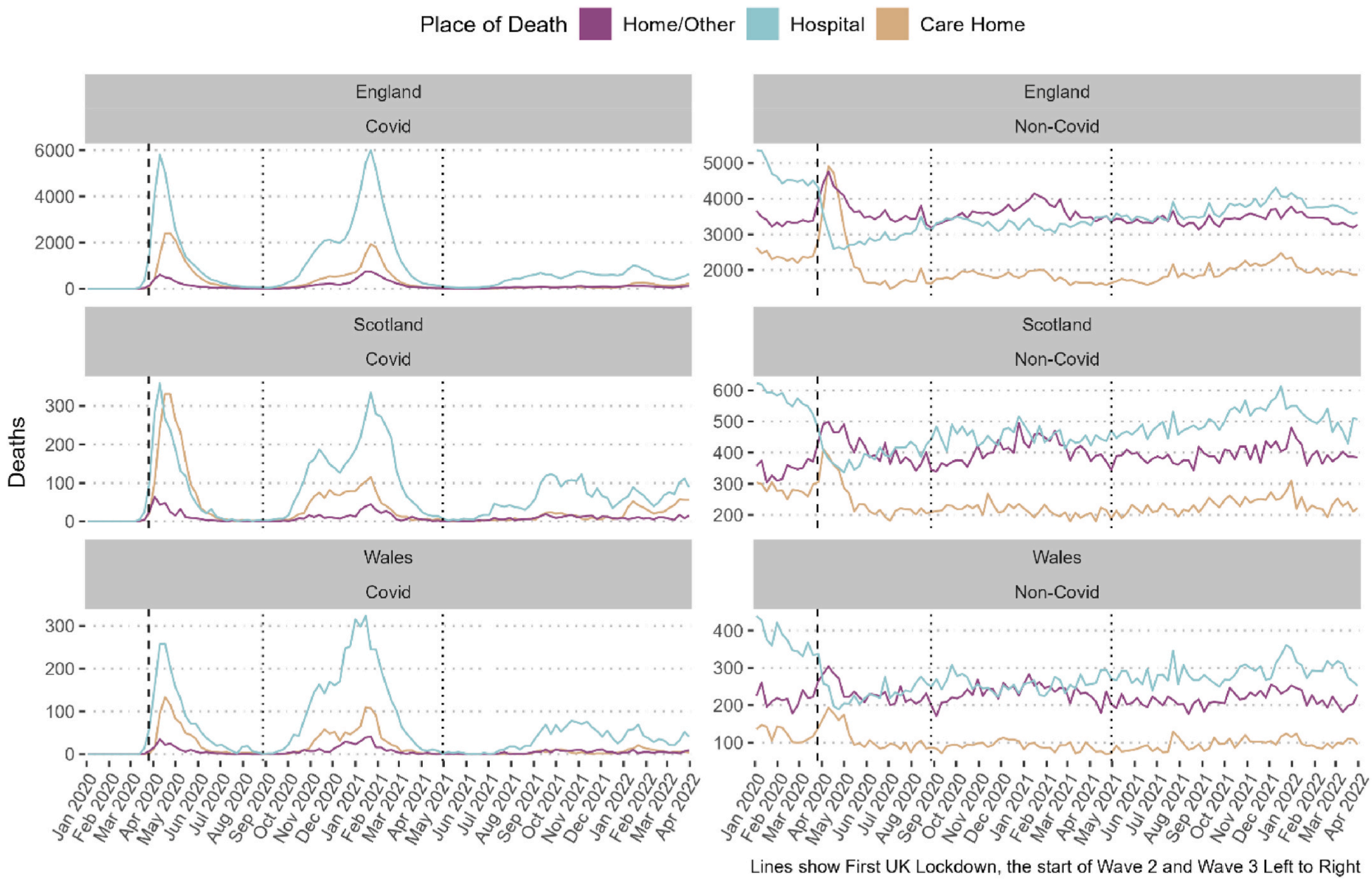

Fig. 1. Weekly number of COVID-19 and non-COVID-19 deaths in England, Scotland, and Wales by place of death, January 2020–March 2022.

were 162,812 deaths in England, 14,183 in Scotland, and 9,973 in Wales, where COVID-19 was the underlying or contributory cause.

The most striking pattern is of the three peaks of COVID-19 deaths corresponding to three waves. Most COVID-19 deaths were in hospitals. A notable exception was the first wave in Scotland when similar numbers of deaths occurred in hospitals and care homes. In all countries, the first and second waves had higher numbers of deaths than the third wave. We saw a spike in non-COVID-19 deaths in care homes in England during the first wave. Similar but much smaller spikes were observed in Scotland and Wales. This indicates that some care home deaths in England may have been misclassified as non-COVID-19 deaths during the first wave. We also observed increases in non-COVID deaths at home and complementary decreases in hospital deaths in all countries during the first wave, suggesting that the lockdown led to more home deaths. We did not see similar spikes in non-COVID-19 mortality during later waves.

Fig. 2 shows the SMR by wave, country, and cause of death. Figure A3 shows the SMR for all-cause mortality by year and country. First, cross-country differences in non-COVID-19 mortality were relatively stable across waves: Scotland had the highest levels, followed by Wales, and England had the lowest. By contrast, COVID-19 mortality showed variation by wave and country not consistent with non-COVID-19 mortality. In the first wave, COVID-19 mortality was significantly higher in England than in Scotland and Wales. In the second wave, both England and Wales had significantly higher levels of COVID-19 mortality than Scotland. In the third wave, COVID-19 mortality was higher in Scotland than in England and Wales, although note that overall, mortality levels were significantly lower than in the first two waves in all three countries.

6.2. Sub-national level

Fig. 3 shows COVID-19 (panel a) and non-COVID-19 (panel b) mortality in LADs in England, Wales, and Scotland across the three waves. In the first two waves, there were greater regional disparities in COVID-19 mortality compared with the third wave. Across all three waves, there were areas of high COVID-19 mortality in parts of Scotland (Glasgow and the Central belt), Northwest England, the Midlands, South Wales, and London, and lower COVID-19 mortality in the Highlands and Border areas of Scotland, Southwest England, and most of Wales. By contrast, non-COVID-19 mortality showed a more pronounced North-South gradient, with most of Scotland, parts of Northern England and North Wales having higher mortality levels. Southeast England generally showed the lowest non-COVID-19 mortality. In Figure A4, we report Local Moran's I's for COVID-19 and non-COVID-19 mortality by local authority districts and wave.

Table 1 shows the results of the Spatial Durbin model for COVID-19 mortality. The marginal effects have been decomposed into direct (own area) and indirect (spillover) impacts. Ethnicity had a significant positive direct impact on COVID-19 mortality across all waves, suggesting that a higher share of ethnic minorities in an area was related to significantly higher COVID-19 mortality in the same area. For example, a one standard deviation increase in the share of ethnic minorities in an area was associated with a 0.14 increase in the SMR. This relationship appeared to be stronger in wave 1 than in later waves, although some caution is needed when comparing the coefficients across waves because standardisation was performed separately for each wave (implying that we only capture relative and not absolute differences in mortality across waves). The indirect impact was not significant, suggesting that the share of ethnic minorities in neighbouring areas did not significantly influence COVID-19 mortality in a given area.

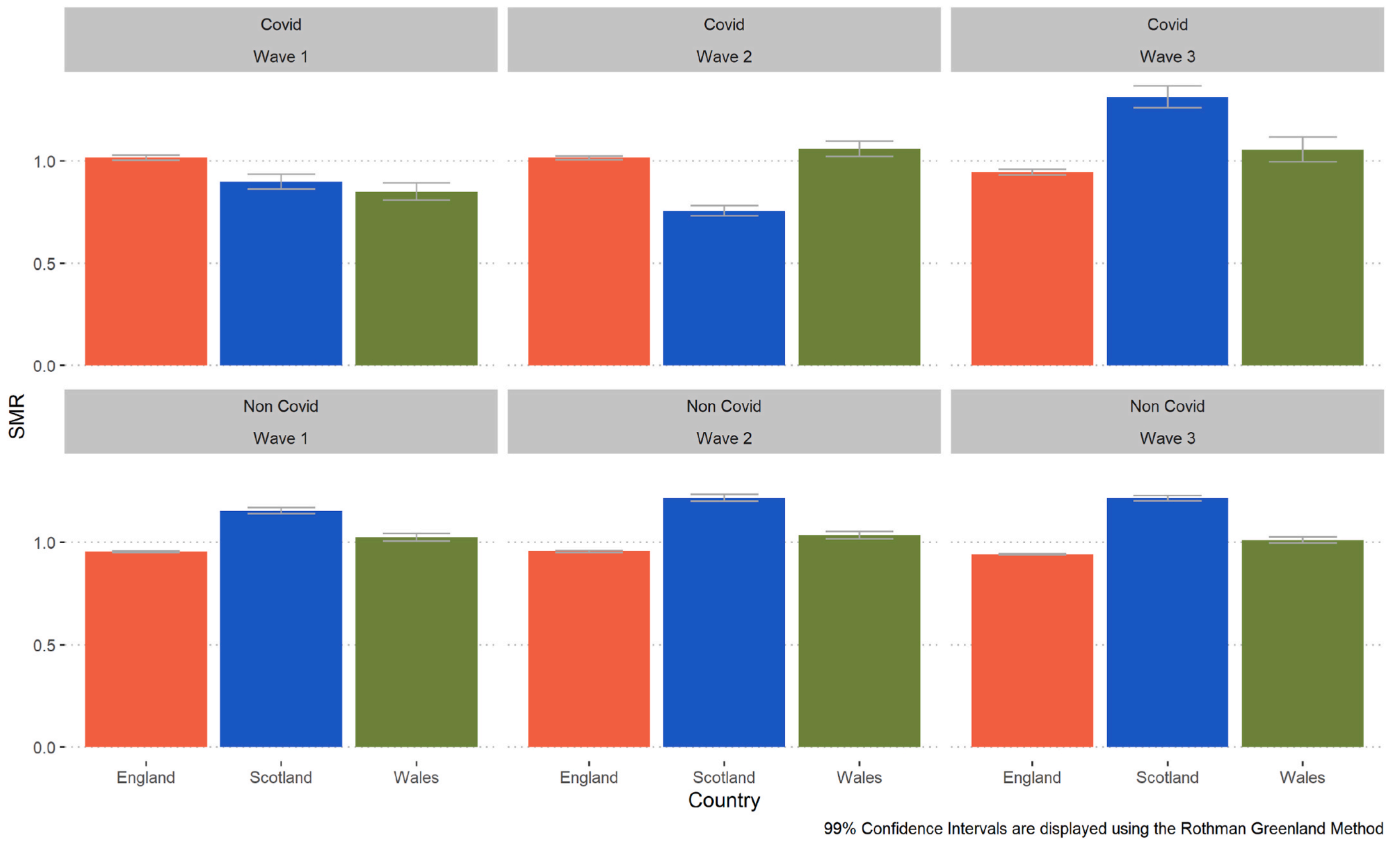

Fig. 2. SMR and 95% confidence intervals by wave and country for COVID-19 and non-COVID-19 mortality
Note: The reference rate (SMR = 1) is the SMR for the whole of Great Britain.

IMD also had a significant positive direct impact on COVID-19 mortality across all waves, suggesting that areas with higher levels of deprivation had higher mortality. This relationship became stronger throughout the waves. The indirect impact of IMD was not significant, indicating that the IMD in neighbouring areas did not influence COVID-19 mortality in a given area. The total impact of IMD was significant and positive.

Population density had a significant positive direct impact on COVID-19 mortality during the first two waves, indicating that more densely populated areas had higher COVID-19 mortality at the start of the pandemic. As the pandemic continued to spread, population density no longer had a significant direct impact on COVID-19 mortality in wave 3 (or the impact, if any, is weak). As opposed to ethnicity and IMD, population density also showed a significant positive indirect impact in the first wave, suggesting significant spillover impacts. That is, COVID-19 mortality in an area was significantly higher if the population density of neighbouring areas was higher, suggesting the spread of the pandemic from big cities to neighbouring areas. The total impact of population density was significant and positive for waves 1 and 2 but not for wave 3. This is largely due to declining spillover impacts across waves, implying that spillover became less important over time as the pandemic has spread.

Interestingly, the variation in COVID-19 mortality across countries was reduced in the multivariate model. Once we accounted for ethnicity, IMD, and population density, there were no differences in COVID-19 mortality across countries in waves 1 or 2. However, Scotland exhibited higher COVID-19 mortality than England and Wales in wave 3.

Finally, we see that the coefficients (rho) for the spatially lagged dependent variable are positive and significantly different from zero for all three waves. This suggests that COVID-19 mortality was spatially clustered in all three waves – areas with high mortality were surrounded by areas with high mortality (even after adjusting for covariates). This supports that the spread of COVID-19 was a spatial process; i.e., spatial proximity played an important role. The results also indicate that any aspatial model would lead to biased estimates, potentially also those, which use individual-level data but do not consider spatial proximity of individuals living in adjacent areas (e.g., central cities and their suburbs).

The results of the models on COVID-19 mortality should be interpreted in the context of mortality due to other causes. Scotland had significantly higher non-COVID-19 mortality in all waves than England and Wales even when ethnicity, IMD, and population density were controlled for (Table 2). These country differences were similar already before the pandemic (see Table A5). The share of ethnic minorities had a negative direct relationship with non-COVID-19 mortality across all waves, indicating that mortality from other causes tends to be lower in areas where the share of ethnic minorities is larger. Area-level deprivation had a consistent positive direct relationship with non-COVID-19 mortality in all waves, meaning that mortality was generally higher in more deprived areas. Population density had a small and significant direct impact on non-COVID-19 mortality in waves 1 and 3, showing urban-rural mortality differences observed in past studies (Levin and Leyland, 2006; Riva et al., 2011). However, the urban-rural differences in all-cause mortality were small compared to those in COVID-19 mortality. Additional analysis revealed (Table A5) that the predictors of mortality were similar before the pandemic to the predictors of non-COVID-19 mortality during the pandemic.

7. Conclusion and discussion

This study investigated spatial patterns and the correlates of COVID-19 mortality across local authority areas in England, Wales, and Scotland during three waves of the pandemic. Our study makes a number of methodological improvements over previous studies. First, we properly

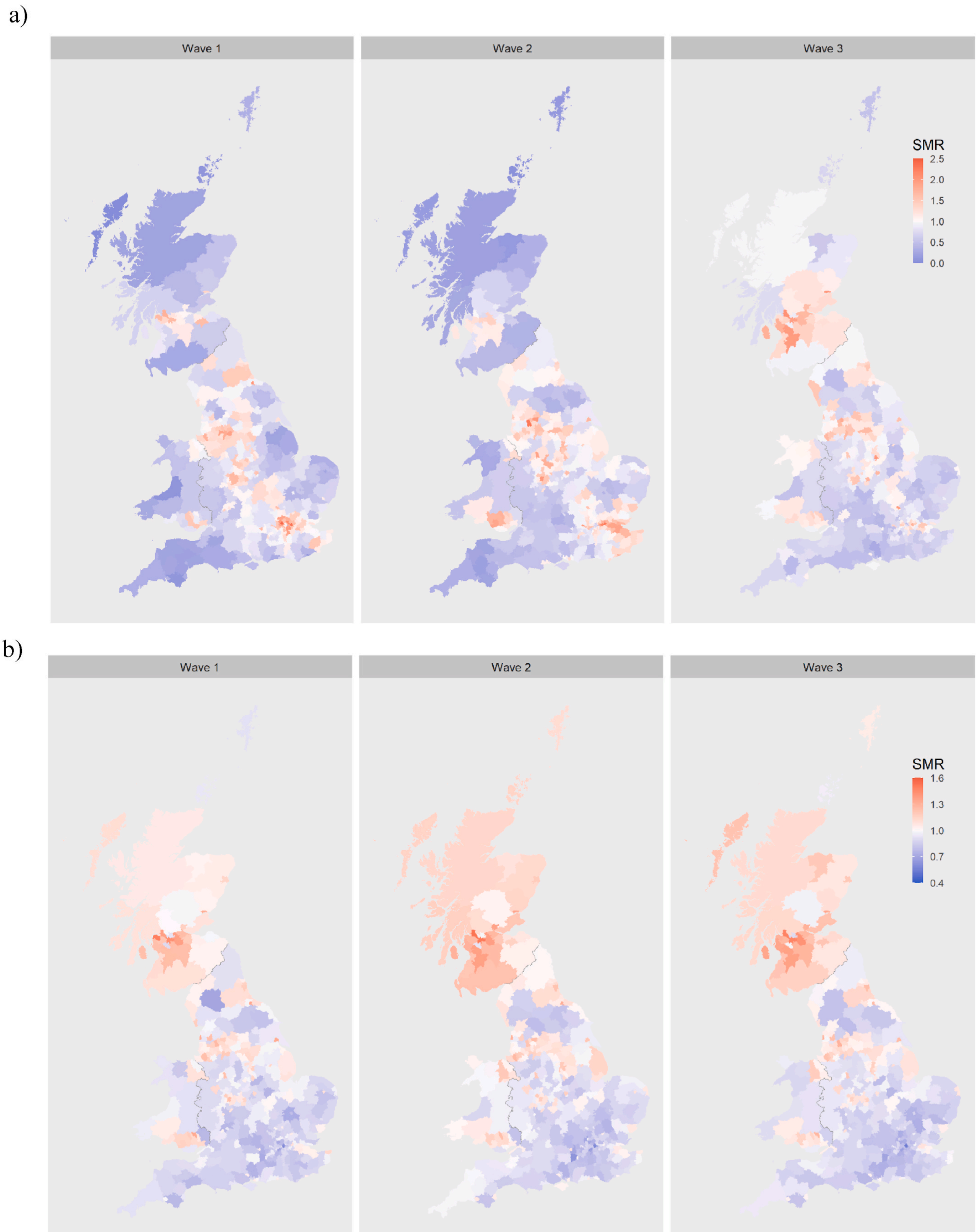

Fig. 3. COVID-19 (panel a) and non-COVID-19 (panel b) mortality (SMR) by local authority districts and wave.

Table 1
Results of the Spatial Durbin model for COVID-19 mortality.

		Wave 1		Wave 2		Wave 3	
		Estimate	P value	Estimate	P value	Estimate	P value
Direct	Ethnicity	0.140	<0.001	0.050	0.010	0.050	0.013
	Deprivation (IMD)	0.090	<0.001	0.160	<0.001	0.210	<0.001
	Population density (log)	0.090	<0.001	0.090	<0.001	0.030	0.053
	Scotland	0.080	0.130	−0.060	0.230	0.210	<0.001
	Wales	−0.010	0.900	−0.020	0.770	0.020	0.641
Indirect	Ethnicity	−0.040	0.600	−0.090	0.340	−0.020	0.637
	Deprivation (IMD)	0.030	0.510	0.030	0.700	0.030	0.417
	Population density (log)	0.260	0.001	0.200	0.080	0.060	0.298
Total	Ethnicity	0.100	0.160	−0.040	0.700	0.020	0.610
	Deprivation (IMD)	0.120	0.030	0.190	0.020	0.240	<0.001
	Population density (log)	0.350	<0.001	0.290	0.020	0.090	0.106
	Scotland	0.190	0.140	−0.210	0.240	0.420	<0.001
	Wales	−0.020	0.900	−0.060	0.770	0.040	0.647
Rho (LR test)		0.601 (99.191)	<0.001	0.760 (213.580)	<0.001	0.535 (66.609)	<0.001
Nagelkerke Pseudo R Squared		0.674		0.702		0.689	

Note: 'Ethnicity' measures the share of individuals who belong to an ethnic minority (i.e., other than 'White British'); 'Deprivation (IMD)' is the index of multiple deprivation which is a proxy for socio-economic status; 'Population density (log)' measures the log of the number of individuals in an area per km^2; Scotland and Wales are dummies indicating the location of the LAD within Great Britain (England is the reference).
Note: Table A3 shows the results with 95% confidence intervals.

Table 2
Results of the Spatial Durbin model for non-COVID-19 mortality.

		Wave 1		Wave 2		Wave 3	
		Estimate	P Value	Estimate	P Value	Estimate	P Value
Direct	Ethnicity	−0.028	<0.001	−0.017	0.010	−0.025	<0.001
	Deprivation (IMD)	0.101	<0.001	0.100	<0.001	0.094	<0.001
	Population density (log)	0.024	<0.001	0.008	0.175	0.013	0.027
	Scotland	0.082	<0.001	0.125	<0.001	0.101	<0.001
	Wales	0.003	0.859	−0.007	0.662	−0.008	0.613
Indirect	Ethnicity	−0.023	0.182	−0.036	0.014	−0.032	0.080
	Deprivation (IMD)	−0.012	0.336	−0.003	0.769	0.002	0.889
	Population density (log)	−0.004	0.846	−0.013	0.427	−0.008	0.719
Total	Ethnicity	−0.051	0.003	−0.052	<0.001	−0.057	0.002
	Deprivation (IMD)	0.088	<0.001	0.097	<0.001	0.096	<0.001
	Population density (log)	0.020	0.335	−0.005	0.777	0.005	0.809
	Scotland	0.174	<0.001	0.223	<0.001	0.239	<0.001
	Wales	0.006	0.861	−0.013	0.668	−0.020	0.621
Rho (LR test)		0.562 (78.343)	<0.001	0.467 (49.287)	<0.001	0.619 (111.250)	<0.001
Nagelkerke Pseudo R Squared		0.771		0.805		0.818	

Note: See Table 1.
Note: Table A4 shows the results with 95% confidence intervals.

account for population age structure using area-level SMR. Second, we assess spatial dependency and spillover impacts using a Spatial Durbin model. Third, we study how both COVID-19 and non-COVID-19 mortality and their correlates have changed over time and place.

Consistent with previous UK studies (e.g., Adin et al., 2022; Breen and Ermisch, 2021; Davies et al., 2021; Harris, 2020; Sun et al., 2021), we find that LADs with a higher share of ethnic minorities, and higher levels of deprivation had higher COVID-19 mortality throughout the pandemic. Our novel contribution is to show variations in these predictors across waves of the pandemic. Over time, the share of ethnic minorities becomes a less important factor for predicting COVID-19 mortality, whereas area deprivation becomes more important. In line with other studies (e.g., Breen and Ermisch, 2021; Ehlert, 2021; Fielding-Miller et al., 2020; Tchicaya et al., 2021), population density is positively associated with COVID-19 mortality both directly (first two waves) or indirectly (first wave) but was not a significant predictor by wave 3. Additionally, between-country disparities in COVID-19 mortality, while at first glance appearing rather stark, are completely accounted for by ethnicity, deprivation, and population density. By wave 3, cross-country patterns of COVID-19 mortality are comparable to the distribution of non-COVID-19 mortality across Scotland, England, and Wales.

Comparing COVID-19 and non-COVID-19 mortality revealed some diverging patterns over time and space. For example, non-COVID-19 mortality shows the well-documented, persistent pattern of Scottish mortality disadvantage, which has been attributed to industrial, employment, and housing patterns adversely affecting population health (McCartney et al., 2012; Walsh et al., 2017). Given this disadvantage, it was surprising that during the first wave, COVID-19 mortality was highest in England, and during the second wave, it was highest in England and Wales. This indicates that Scotland did much better than would have been expected, given its usual mortality profile. Scotland's advantage attenuated after adjusting for ethnicity, IMD, and population density, suggesting that during the early COVID-19 waves, Scotland's lower population density and relative rurality contributed to their lower COVID-19 mortality. This is supported by the fact that lower Scottish COVID-19 mortality rates were observed in more rural areas, especially the Highlands; the central belt actually showed relatively high COVID-19 mortality at every wave. By the third wave, when vaccination uptake played a more important role and population density a less important role in mortality dynamics, the typical mortality pattern had returned, and Scotland experienced persistent disadvantages in

COVID-19 and non-COVID-19 mortality alike. The results also highlighted that urban-rural differences were more important for COVID-19 mortality than for mortality from other causes. Some highly urbanised regions, such as London, show persistently high COVID-19 deaths in every wave, despite lower mortality from other causes.

It is a paradox that areas with a larger share of ethnic minorities had higher COVID-19 mortality (net of deprivation and population density) but lower mortality due to other causes. The latter finding is related to the well-documented migrant mortality advantage (Wallace and Kulu, 2015) attributable in part to the 'healthy migrant effect' and potentially better health behaviours among immigrants than native populations. The reverse relationship between the share of ethnic minorities and COVID-19 mortality deserves further exploration. Higher COVID-19 mortality among ethnic minorities in early waves is likely to be at least partly related to transmission, such as a higher probability of infection due to living in multi-generational or larger households and working in occupations with greater exposure to the virus (Mutambudzi et al., 2021; Wing et al., 2022). In the third wave, with protection from vaccines, areas with a higher share of ethnic minorities saw their risk attenuate, but not completely. This residual disadvantage could be related to higher rates of vaccine hesitancy in ethnic minority groups (Kamal et al., 2021; Robertson et al., 2021). Alongside this, ethnic minorities in many areas are more likely to be disadvantaged in terms of socioeconomic status and housing conditions, which might exacerbate their risks. Given that the long-term effects of the COVID-19 infection include higher risks of cardiovascular disease, long COVID, and other chronic illnesses (Lopez-Leon et al., 2021), future ethnic minority health advantages may be partially eroded. Therefore, we should continue to unpick the mechanisms, as they help us understand and address ethnic health inequalities both for COVID-19 and future pandemics.

Area deprivation has become a more important predictor of COVID-19 mortality over time as more mechanistic transmission factors (e.g., population density) have become less important. In wave 3, when vaccination coverage should have levelled social inequalities, deprivation has become the most important factor in predicting COVID-19 mortality. Factors such as housing, unemployment, and healthcare systems, operate on COVID-19 risks through pathways of unequal exposure, transmission, vulnerability, and susceptibility (Bambra, 2022). In the first wave of the pandemic in the UK, a decomposition analysis showed that the impact of deprivation on COVID-19 deaths operated mainly through increased risks of transmission (Albani et al., 2022). In later waves, the impact of deprivation may also operate via increased vulnerability created by vaccine hesitancy, which is most common among lower-educated subgroups (Robertson et al., 2021). Regardless of the mechanisms, our study provides strong evidence that tackling the wider social determinants of health is key to alleviating medium- and long-term COVID-19 inequalities (McGowan and Bambra, 2022). Future research should study how area-level deprivation and COVID-19 health disparities accumulate over time, how they might intersect with the current cost-of-living crisis to widen social inequalities, and how multiple domains of deprivation intersect at scales other than area or individual level, for example, cluster in households and families (Mikolai et al., 2020).

Our study has some limitations. First, it would have been useful to be able to account for other potentially important area-level factors, such as vaccination rates or the availability of healthcare services. Although data on vaccinations are available by sex, age, and LAD in England and Scotland, these are not available for Wales. Most importantly, the biggest challenge is to include information on vaccination, given that vaccines became available at a different pace across age groups and areas. Second, using a more nuanced measure of health vulnerabilities than what is included in the IMD (i.e., health deprivation and disability) could have been useful to better account for the underlying health status of the population in each area, which is likely to have a large impact on COVID-19 mortality. Third, individual-level population data would be the ideal data source to understand the drivers of COVID-19 mortality. However, in the UK and in many other countries, such data are not available. Finally, we studied COVID-19 mortality at the level of Local Authority Districts, but spatial patterns could vary within LADs. This could be a topic for future research.

In conclusion, our study provides the most up-to-date, methodologically advanced spatial analysis of patterns of COVID-19 mortality over three waves of the pandemic in a high-income country. It brings a longitudinal approach to understanding how risk factors and regional disparities evolve over the course of the pandemic. Our results not only have implications for understanding contemporary health disparities and the medium-to long-term impact of the COVID-19 pandemic on health inequalities but also for preventing inequalities during future pandemics.

Ethics statement: This study has received ethical approval from the School of Geography & Sustainable Development Ethics Committee, acting on behalf of the University Teaching and Research Ethics Committee of the University of St Andrews (approval code: GG16655).

Author contributions

Mikolai: Conceptualization, Supervision, Writing – original draft, Writing – review & editing; **Dorey**: Conceptualization, Formal analysis, Writing – original draft, Writing – review & editing; **Keenan**: Conceptualization, Supervision, Writing – original draft, Writing – review & editing; **Kulu**: Conceptualization, Supervision, Writing – review & editing.

Declaration of competing interest

None.

Data availability

The data are publicly available and cited in the manuscript.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.socscimed.2023.116330.

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