Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

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COVID-19 and deprivation amplification: An ecological study of geographical inequalities in mortality in England

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ABSTRACT

'Deprivation amplification' is used to understand the relationship between deprivation, scale and COVID-19 mortality rates. We found that more deprived Middle Super Output Areas (MSOAs) in the more deprived northern regions suffered greater COVID-19 mortality rates. Across England, the most deprived 20% of MSOAs had higher mortality than the least deprived (44.1% more COVID-19 deaths/10,000). However, the most deprived MSOAs in the north fared worse than equally deprived areas in the rest of England (14.5% more deaths/10,000, beta = 0.136, $p < 0.01$). There was also strong evidence of spatial clustering and spill-overs. We discuss these findings in relation to 'deprivation amplification', the 'syndemic pandemic', and the health and place literature.

1. Background

Socio-economic and ethnic inequalities in case, hospitalisation and mortality rates from COVID-19 have been demonstrated across many countries (Bambra et al., 2020a, 2021). This emergent - but already fairly extensive international literature - has found that people of lower socio-economic status (SES) have mortality rates more than double those of higher SES (Barceló and Saez, 2021). Inequalities between different ethnic groups have been particularly high, whereby people of Black, Asian and Minority Ethnic backgrounds have suffered a higher burden of disease and a much higher death rate from COVID-19 than their white counterparts (Public Health England, 2020; Katikireddi et al., 2021; Nazroo and Becares, 2020).

Geographical inequalities in COVID-19 have also been extensively studied (Welsh et al., 2021; McGowan and Bambra, 2022) and research in various global contexts has found that the more economically and socially deprived neighbourhoods, municipalities and regions have fared worse (Bambra et al., 2020b; Welsh et al., 2021; Chen and Krieger, 2021; Morrissey et al., 2021; McGowan and Bambra, 2022). For example, research in the USA found that the most deprived counties suffered up to twice the mortality rates of the least deprived counties in the first wave (Chen and Krieger, 2021). Similarly, in England, research found that deprivation was highly associated with COVID-19 cases (Morrissey et al., 2021) and that more deprived local authorities started recording COVID-19 deaths earlier and saw faster increases in their death rates than more affluent areas (Welsh et al., 2021). Research into regional inequalities has found that COVID death rates were much higher in the three Northern regions of England during the first year of the pandemic (Munford et al., 2021).

These geographical inequalities in the COVID-19 pandemic have been explained through the syndemic pandemic concept. A syndemic describes 'a set of closely intertwined and mutual enhancing health problems that significantly affect the overall health status of a population within the context of a perpetuating configuration of noxious social conditions' (Singer, 2000). Deprivation - which is a measure of the social determinants of health – results in multiple, interacting and additive adverse risk factors for COVID-19 mortality (Bambra et al., 2020a). Bambra et al. (2020a) use this framing to outline five potential pathways leading to unequal pandemics: unequal exposure (resulting from less ability to shield from infection in more deprived areas); unequal transmission (increased risk of community spread infection for people living in more deprived areas); unequal vulnerability (increased risk of mortality from the higher burden of non-communicable diseases in deprived areas); unequal susceptibility

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(increased risk of more severe disease for people in deprived areas); and unequal treatment (inequalities in access to – and uptake of - health care treatment and preventative services e.g. vaccines) (Bambra et al., 2020a; Bambra et al., 2021b; Todd and Bambra, 2021).

However, geographical research has examined either neighbourhood-, municipality- or regional-level inequalities (McGowan and Bambra, 2022). There has been little exploration of the potential interactions between these different geographical scales in terms of shaping inequalities in the pandemic (notable exceptions include Griffith et al., 2021 in relation to the first wave of 2020 and Harris, and Brunsdon, 2021 in relation to the relative exposure of ethnic minority communities). The concept of deprivation amplification is potentially relevant to thinking about such influences. The deprivation amplification theory draws on the wider health geography literature on health and place - particularly the *context-composition-relational* debate (Cummins et al., 2007; Bambra, 2016). The compositional view argues that the socio-demographic characteristics of who lives in a place determines its health outcomes (Bambra, 2016). The contextual approach highlights that it is what a place is like (the economic, social, and physical environments) that matters for the health of its residents *(ibid.)*. Compositional and contextual aspects of place interact relationally (Macintyre et al., 2002): the characteristics of individuals are influenced by the characteristics of the area (Cummins et al., 2007) with places constituting socio-material assemblages of human and non-human materialities (Powell et al., 2020; Fox and Powell, 2021). The literature on health and place has also begun to consider the influence of macro-level political, economic and institutional factors (Bambra et al., 2019).

Engaging with this debate, the deprivation amplification hypothesis asserts that the negative health effects of individual-level low socio-economic status (SES) (composition) are amplified (relational) for those living in more deprived areas (context) (Macintrye et al., 1993). In the literature, this concept has largely been applied to examining whether differential access to resources (context) between local areas impacts on the relationship between low SES (compositional) and health (Macintyre et al., 2008). Most notably this work has examined whether individual-level SES inequalities in physical activity are compounded by area-level characteristics (Macintyre, 2007; Schneider et al., 2019). In this regard, the concept of deprivation amplification has been subject to some debate. For example, some studies have found support for the thesis – that individual SES inequalities in physical activity are higher in more deprived areas (Macintyre et al., 2008) whilst others have not (Macintyre, 2007; Schneider et al., 2019). However, beyond the contextual effects literature, deprivation amplification has seldom been used to explore interactions between different scales of place – for example by examining differences in the health profiles of more deprived neighbourhoods or local authorities within more - or less - deprived regions.

There are well established and longstanding regional inequalities in health in England (Bambra, 2016). In the mid-19th century, life expectancies in Northern cities were four years lower than in southern cities (Szreter and Mooney, 1998), and today, there is a two-year difference in average life expectancy between the three Northern regions (North East, North West and Yorkshire and Humber) and the rest of England (Public Health England, 2019). People in the North consistently have higher mortality rates and lower life expectancy than those in the south - across all socio-economic groups, all ages and amongst both men and women (Bambra et al., 2014). Premature death rates are now 20% higher for those living in the North and since 1965 this amounts to over 1.5 million Northerners dying before their southern counterparts (Hacking, 2011). Socio-economic inequalities in health are also larger in the North (Doran et al., 2004). England's regional health inequalities are amongst the largest in Europe (Bambra et al., 2014) and there is also evidence that they are increasing - particularly amongst younger adults (Kontopantelis et al., 2018). Life expectancy in deprived southern local authorities is also higher than in similarly deprived Northern areas – suggesting a process of regional deprivation amplification (Whitehead et al., 2014). Much of this North-South health divide arises because the three Northern regions are more deprived than the other regions of England (Whitehead et al., 2014; Bambra 2016).

No study has investigated deprivation amplification in the context of the COVID-19 pandemic. We set out to 'test' the 'deprivation amplification' hypothesis and examine whether – or not - COVID-19 mortality rates by deprivation differ by region in England. To do this, the study uses Middle Super Output Area (MSOA) level COVID-19 mortality data from England – stratified by MSOA deprivation and by English Government Office Region. Specifically, it examines whether more deprived MSOAs (the bottom quintile) in the more deprived Northern regions suffered greater COVID-19 mortality rates during the first fourteen months of the pandemic (between March 2020 and April 2021) than those in less deprived regions ('the South'). As COVID-19 is an infectious disease, the analysis also uses spatial-lag models to examine whether the COVID-19 mortality rate and level of deprivation in neighbouring MSOAs had any impact (or 'spill-over' effects) on COVID-19 mortality rates of each nearby MSOA.

2. Methods

2.1. Research Question

1. Were there regional inequalities in COVID-19 mortality rates across the nine regions of England? In particular, was there a North/South divide in COVID-19 mortality rates?
2. Did more deprived areas (MSOAs) do worse across the country? Or did deprived areas in the North do worse than deprived areas in the South?
3. Is the level of COVID-19 mortality in an MSOA affected by the COVID-19 mortality rate and the level of deprivation in neighbouring (or contiguous) MSOAs?

2.2. Data

To answer the above research questions, we combined data at Middle Super Output Area (MSOA)-level on mortality attributable to COVID-19, the age structure, the ethnicity structure, and the level of deprivation.

Super output areas are artificial statistical geographical units created by the Office for National Statistics to improve and harmonise analysis (ONS, 2011). They are based on the 2011 Census. There are three types – output areas (OAs), lower super output areas (LSOAs) and middle super output areas (MSOAs). OAs are based on postcodes and the majority of OAs (79.6%) contain between 110 and 139 households. OAs are then used to form LSOAs which range from 400 to 1200 households. MSOAs are in turn created by combining between four and six LSOAs on average. MSOAs contain a minimum of 5000 and a maximum of 15000 people and a minimum of 2000 and a maximum of 6000 households. We used MSOAs because this is the smallest geographical scale at which COVID-19 mortality data is publicly available.

Mortality attributable to COVID-19 were available from the Office for National Statistics (ONS, 2021). Data were recorded as counts of deaths in the 14-month period from March 2020 to April 2021. Age-standardised mortality rates were not provided at MSOA-level and so we constructed the mortality rate per 10,000 population by dividing the total count of deaths attributable to COVID-19 by the 2019 population estimate and multiplying by 10,000. The ONS classified deaths directly attributable to COVID-19 if COVID-19 was the underlying (main) cause of death. This classification would exclude some deaths where the underlying cause was not COVID-19 but COVID-19 was mentioned on the death certificate as a contributory cause of death. Data on MSOA population estimates were reported by the ONS. We used the (natural) logarithm of the COVID-19 mortality rate per 10,000 population as the raw data were not normally distributed.

Given the association between increasing age and increasing mortality – especially for COVID-19 deaths, we additionally obtained

information on the age structure (in bands ranging from 0 to 4 years–90 years and over) from the 2011 Census. Likewise, as various studies have shown a strong association between ethnicity and increased risk of COVID-19 mortality, we also included the ethnicity structure. We used the Office of National Statistics' five broad Census categories: White and White British (English, Welsh, Scottish, Northern Irish or British Irish, Gypsy or Irish Traveller, Roma, Any other White background), Black and Black British (Caribbean, African, Any other Black, Black British, or Caribbean background), Asian and Asian British (Indian, Pakistani, Bangladeshi, Chinese, Any other Asian background), people with a Mixed ethnicity (White and Black Caribbean, White and Black African, White and Asian, Any other Mixed or multiple ethnic background), and Other (Arab, Any other ethnic group) for areas from the 2011 Census. We did this because whilst it is possible to obtain more granular ethnicity data, many cells are 'suppressed' due to small numbers of observations in some MSOAs. We therefore used the five-category definition of ethnicity so as not to encounter statistical problems associated with missing, or censored, data. In each case, the data indicate the percentage of the MSOA population that belong to each category. We use data from the 2011 Census as it is the most complete and does not rely on statistical modelling (age data for non-Census years). Ethnicity data at MSOA-level is not modelled, and is only available in Census years. Ethnicity data are available at larger geographies (such as local authorities), but that is too large for use here.

As urban-rural differences in mortality are often significant (Congdon, 2021), we additionally obtained information of the rurality/urbanity of each MSOA using data from the ONS. Each MSOA is assigned to one of eight categories which we condensed to five: 1) Rural town and fringe (including 'in a sparse area'), 2) Rural village and dispersed areas (including 'in a sparse area'), 3) Urban cities and towns (including 'in a sparse area'), 4) Urban major conurbations, and 5) Urban minor conurbations. For categories 1 3) we combined the 'main' category with the additional 'in a sparse area' as the latter often had very few MSOAs in. However, the main results are robust to keeping all eight categories.

Finally, deprivation was assessed using the 2019 version of the Index of Multiple Deprivation (IMD) obtained for each MSOA from https://research.mysociety.org/sites/imd2019/about/. IMD is the most commonly used measure of area-level deprivation in England. It produces a ranking of areas in England based on relative local scores for: income, employment, health, education, crime, access to services and living environment (DCLG, 2019). To obtain MSOA scores and ranks from data available at LSOA level, population weighted average score of LSOAs within each MSOA were calculated. Each MSOA was then ranked from 1 (most deprived) to 6791 (least deprived). For ease, we split deprivation into five quintiles ranging from 1 (least deprived 20% of MSOAs) to 5 (most deprived 20% of MSOAs).

2.3. Analysis

We started by summarising the variables for the 6791 MSOAs in England. We additionally summarised the variables according to whether the MSOA was in the North of England (defined as the North East, the North West, or Yorkshire and the Humber) or the rest of England (defined as East Midlands, West Midlands, East of England, South East, South West, or London). We present graphs of the average MSOA COVID-19 mortality rate (per 10,000 population) by region. We then present a graph showing the COVID-19 mortality rate by North/rest of England and deprivation quintile, including confidence intervals. The 95% confidence interval is calculated by applying the formula mean $\pm$ 1.96 $\times$ s.e, where s.e. is the standard error of the mean.

To examine if there was a difference in COVID-19 mortality rates after accounting for possible confounding factors (age, ethnicity, urbanity and deprivation) between the North and the rest of England we estimated a multivariate linear regression model:

$$y_m = \beta North_m + \gamma \boldsymbol{X}_m + \delta \boldsymbol{IMD}_m + e_m \quad (1)$$

In this set-up, y refers to (the natural logarithm of the) COVID-19 mortality rates per 10,000. North is a binary indicator equal to one if an MSOA is in the North of England and equal to zero if an MSOA is in the rest of England. **X** is a vector containing information relating to the % of each MSOA's population in each age band and each ethnicity group as well as information on the urban/rural status of the MSOA. These variables are included separately and are also interacted with the North dummy variable to allow for interaction effects. **IMD** is a series of four indicators relating to each IMD quintile (the first – least deprived – is the reference category). Again, these IMD indicator variables are included on their own but are also interacted with the North dummy variable to allow for differential effects of deprivation in the two areas considered. The error term e is assumed to be normally distributed and i.i.d. This is shown to hold true when we use the logged outcome. Subscript m refers to MSOA m = 1, 2, …, 6791.

Because we have taken the natural logarithm of the dependent variable, and our main exposure (North) is a binary variable, we need to interpret the 'excess' Northern mortality in percentage terms. We do this by applying the formula $100 \times (e^{\beta} - 1)$, where β is the parameter on North. In Tables, we present the raw coefficients. However, we also provide the percentage interpretation for key parameters in the accompanying text.

However, the multivariate linear regression models ignore the possibility of spatial-dependencies that might exist between neighbouring MSOAs. We therefore allowed for this possibility to estimating spatial lag models of the form:

$$y_m = \beta North_m + \gamma \boldsymbol{X}_m + \delta \boldsymbol{IMD}_m + \rho W_{m,n} y_n + \boldsymbol{\lambda} W_{m,n} \boldsymbol{IMD}_n + u_m; \quad (2)$$

where $u_m = \varepsilon W_{m,n} u_n + \mu_m$

In this spatial model, subscript n≠m refers to the neighbouring MSOAs of MSOA m. The error term u includes a spatially correlated component (u_n; i.e. the error term of neighbouring MSOAs) and an orthogonal component μ_m. The term ε models the spatial error autocorrelation structure. The coefficients of interest can be consistently estimated using a generalised two-stage least squares approach. The defining feature of the above model is the square 'spatial weights' matrix W. Here, W is specified as a contiguity matrix, such that the element in the m-nth position, w_{mn}, takes the value 1 if MSOAs m and n have a common border and 0 otherwise. We specify Queen's criteria for defining contiguity, although the results are robust to Rook's criteria.

The set-up above contains three spatial elements. First, it allows the mortality rates of neighbouring MSOAs to affect the mortality rate of each MSOA, captured by the $\rho W_{m,n} y_n$ term. Second, it allows the level of deprivation in neighbouring MSOAs to affect the mortality rate of each MSOA, captured by the $\lambda W_{m,n} IMD_n$ term. Finally, it allows there to be correlated 'shocks' that are experienced by neighbouring MSOAs, captured by the $\varepsilon W_{m,n} u_n$ component of the error term.

Our spatial model assumes that there exists spatial dependencies. This assumption does not only affect the estimation of the model, but also the interpretation of the coefficients. The model produces *Average Direct Effects* (the average across all MSOAs in the sample of the ["own"] effect of the IMD quintile in MSOA m on the COVID-19 mortality in the same MSOA m, including the potential feedback effect from neighbouring MSOAs which are affected by the level of COVID-19 mortality in MSOA m); *Average Indirect Effect* (the average across all MSOAs in the sample of the effect on COVID-19 mortality for MSOA m resulting from other MSOAs n ≠ m, indirectly affecting COVID-19 mortality in MSOA m as a result of spatial dependencies through shared borders); and the *Average Total Effect* (the sum of the two above [Average Direct Effect + Average Indirect Effect]). We outline how each is defined in Appendix A.

To test whether it is necessary to perform a spatial analysis, we calculate Moran's I:

$$I = \frac{N}{S} \times \frac{\sum_{m=1}^{N}\sum_{n=1}^{N} W_{mn}(y_m - \bar{y})(y_n - \bar{y})}{\sum_{m=1}^{N}(y_m - \bar{y})^2}$$

where N (=6971) is the number of MSOAs indexed by m and n. y is the (logged) outcome from unit m or n and $\bar{y}$ is the mean of the (logged) outcome across all units. W is the contiguity matrix as defined above, and S is the sum of all possible weights matrices for all m and n. The expected value of I under the null hypothesis of no spatial autocorrelation is $E[I] = \frac{-1}{N-1}$. The test has been widely used to test for the existence of spatial autocorrelation (Francetic and Munford, 2021). We further implement the test suggested by Hepple (1998) for use on regression residuals and the test statistics, and outcomes, are qualitatively very similar.

3. Results

Descriptive statistics for key variables are shown in Table 1. The crude average COVID-19 mortality rate in the fourteen-month period between March 2020 and April 2021 in England was 21.43 per 10,000 (95% C.I.: 21.16 to 21.70). Note that this rate is not age standardised and it is the total rate, not an annual approximation. The average COVID-19 mortality rate was 3.25 deaths per 10,000 higher in the North than in the rest of England (95% C.I.: 2.65 to 3.84); 23.74 (95% C.I.: 23.25 to 24.23) vs. 20.49 (95% C.I.: 20.17 to 20.81) per 10,000. Regional COVID-19 mortality rates are shown in Fig. 1 (panel (a)). The North West had the highest COVID-19 mortality rate (25.5 per 10,000) and the North East had the second highest (24.2 per 10,000). These are both nearly double the COVID-19 mortality rate in the South West (13.4 per 10,000). Panel (b) of Fig. 1 shows the COVID-19 mortality rate by IMD quintile. The most deprived 20% of areas had higher crude mortality rates (24.5 per 10,000) than the least deprived 20% of areas (19.7 per 10,000).

The North is less ethnically diverse than the rest of England, where 91.3% of the population are White, compared to 84.4% in the rest of England. In the North, Black, Asian and Mixed ethnic groups make up 1.20%, 5.52% and 1.43%, respectively, compared to 4.09%, 7.95% and 2.49% in the rest of England.

There is more deprivation is the North of England than in the rest of England. 34% of the MSOAs in the North are in the most deprived quintile, compared to 14% in the rest of England. Accordingly, 14% of the MSOAs in the North are in the least derived (or most affluent) quintile, compared to 22% in the rest of England.

From Fig. 2 and Table 2, it can be seen MSOAs in the most deprived quintile in the North had higher crude COVID-19 mortality rates than MSOAs in the most deprived quintile in the rest of England, and that this difference was statistically significant (represented by non-overlapping confidence intervals). This is true for quintiles 2, 3, and 4 too. Although MSOAs in the least deprived quintile in the North had higher COVID-19 mortality rates than MSOAs in the least deprived quintile in the rest of England, this difference was not statistically significant. Similar data is presented for all regions in Appendix B.

Table 3 reports the estimated coefficients from linear models (Equation (1)) where we add in covariates sequentially. From the simple adjusted linear model (column 1), it can be seen that unadjusted COVID-19 mortality rates were higher in the North (beta = 0.198 equivalent to 21.5% higher; $p < 0.001$). When information on the age structure and ethnic composition of the MSOA was included, the main effect of North increased to beta = 0.396, or 48.5% more deaths per 10,000 ($p < 0.001$). MSOAs with larger percentages of Asian/British Asian and Black (including African, Caribbean, and Black British) populations experienced higher mortality rates. The age effects are as expected but omitted from the tables due to brevity.

In column 3, we add in urbanity (and its interaction with North). In this specification MSOAs in the North has higher mortality of around 34.4% (beta = 0.296, $p < 0.001$). Urban areas tended to have higher COVID-19 mortality and there was very little evidence of differential effects of urbanity between the North and rest of England.

Finally, in column (4) we present the full model where we additionally account for deprivation and its interaction with North. Northern MSOAs had 23.1% more deaths per 10,000 (beta = 0.208, $p < 0.001$) even after accounting for age, ethnicity, and deprivation. COVID-19 mortality rates exhibited a monotonic relationship with deprivation (i.e. more deprived areas had higher mortality rates than areas with less

Table 1
Summary statistics; pooled and by North/Rest of England.

Variable	England (N = 6791)		North (N = 1956)		Rest of England (N = 4835)	
	Mean/% [95% C. I.]	Std. dev.	Mean/% [95% C. I.]	Std. dev.	Mean/% [95% C. I.]	Std. dev.
COVID-19 mortality rate (per 10,000)	21.43 [21.16 to 21.70]	11.36	23.74 [23.25 to 24.23]	11.08	20.49 [20.17 to 20.81]	11.34
% in age band (in years)						
Age 0 to 4	6.20	1.67	6.06	1.66	6.26	1.68
Age 5 to 7	3.43	0.78	3.39	0.79	3.45	0.78
Age 8 to 9	2.15	0.48	2.13	0.48	2.17	0.48
Age 10 to 14	5.82	1.16	5.79	1.09	5.83	1.19
Age 15	1.23	0.29	1.24	0.26	1.23	0.30
Age 16 to 17	2.49	0.55	2.50	0.46	2.48	0.58
Age 18 to 19	2.54	1.77	2.71	2.06	2.47	1.64
Age 20 to 24	6.60	4.25	6.85	5.13	6.51	3.83
Age 25 to 29	6.74	3.09	6.46	2.60	6.85	3.26
Age 30 to 44	20.49	3.86	19.56	2.66	20.87	4.20
Age 45 to 59	19.58	3.20	20.05	3.29	19.39	3.15
Age 60 to 64	6.09	1.84	6.33	1.67	5.99	1.89
Age 65 to 74	8.75	2.99	9.04	2.66	8.64	3.10
Age 75 to 84	5.62	2.10	5.74	1.83	5.58	2.19
Age 85 to 89	1.49	0.68	1.44	0.55	1.51	0.73
Age 90 and over	0.77	0.44	0.71	0.35	0.80	0.47
% in ethnicity group						
White	86.34	18.00	91.26	14.13	84.35	18.99
Mixed	2.18	1.77	1.43	1.19	2.49	1.87
Asian	7.25	12.06	5.52	11.53	7.95	12.19
Black	3.26	6.32	1.20	2.71	4.09	7.12
Other	0.97	1.64	0.60	1.20	1.12	1.76
Urban/Rural						
Rural town and fringe	8.95%		8.54%		9.12%	
Rural village and dispersed	8.60%		5.01%		10.05%	
Urban city and town	43.45%		32.98%		47.69%	
Urban major conurbation	35.33%		45.96%		31.02%	
Urban minor conurbation	3.67%		7.52%		2.11%	
% in IMD quintile						
5 (most deprived)	20%		34%		14%	
4	20%		21%		20%	
3	20%		16%		22%	
2	20%		15%		22%	
1 (least deprived)	20%		14%		22%	

Notes: The crude regional mortality rate is the population-weighted average of each MSOA within that region. Each MSOA's mortality rate is defined as the total number of deaths between March 2020 and April 2021 divided by the population estimate from 2019, expressed per-10,000 population. The mortality rates are not age-standardised. In addition, they are 14-month totals, not annual approximations. The North is defined as the North East, North West, and Yorkshire and the Humber. The rest of England is the remaining six regions of England. The 95% confidence interval is calculated by applying the formula mean ± 1.96 × s.e, where s.e. is the standard error of the mean.

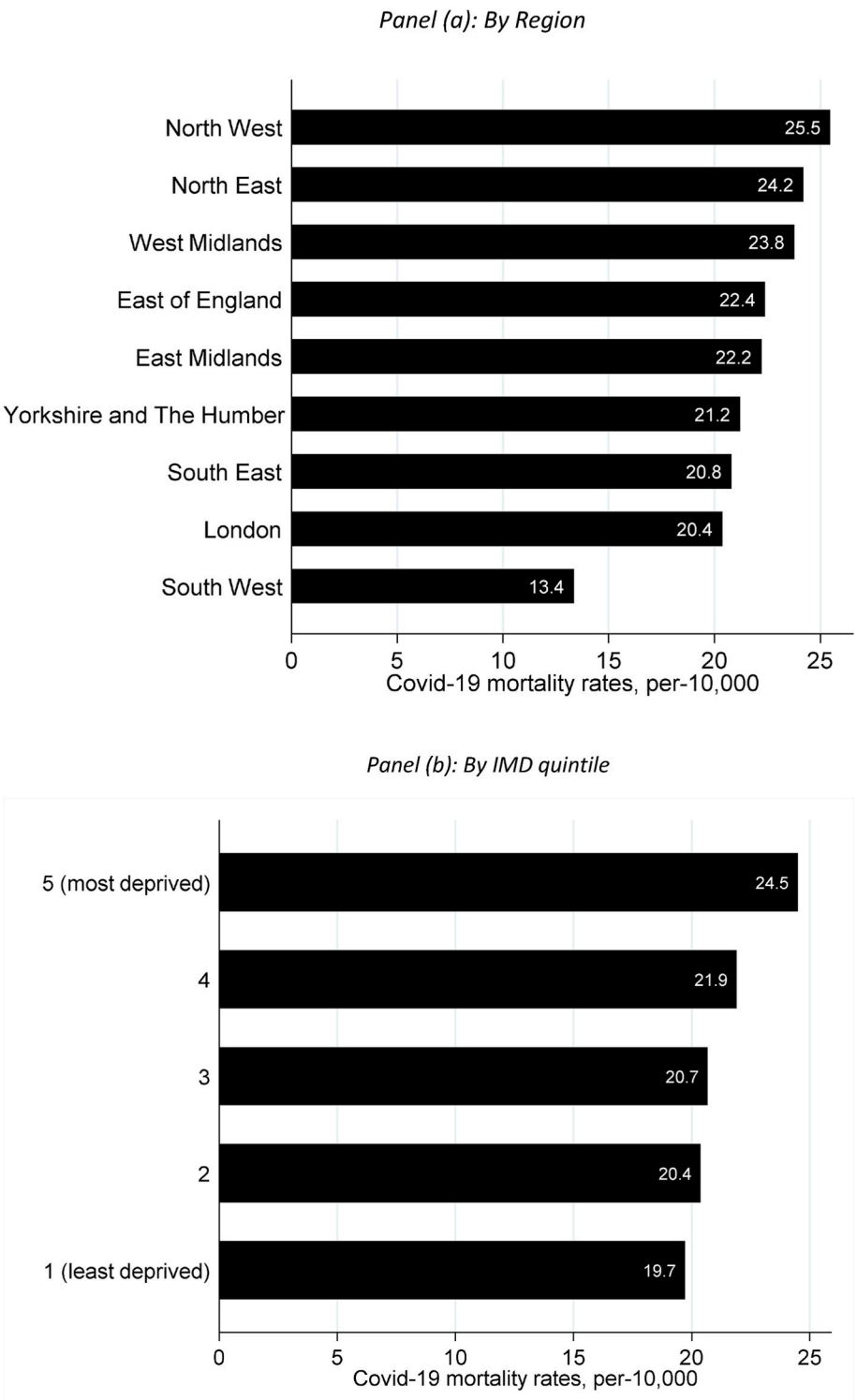

Fig. 1. Crude COVID-19 mortality rates, by region (panel (a)) and deprivation quintile (panel (b)).
Notes: The crude regional mortality rate is the population-weighted average of each MSOA within that region. Each MSOA's mortality rate is defined as the total number of deaths between March 2020 and April 2021 divided by the population estimate from 2019, expressed per-10,000 population. The mortality rates are not age-standardised. In addition, they are 14-month totals, not annual approximations.

deprivation, and each quintile had higher mortality than the one immediately below it). The most deprived quintile of MSOAs experiencing 44.1% more COVID-19 deaths per 10,000 population that the least deprived MSOAs (beta = 0.365, $p < 0.001$). MSOAs in quintiles one to four in the North had similar mortality to the equivalently deprived MSOAs in the rest of England. However, MSOAs in the most deprived quintile in the North had an additional 14.5% higher mortality than the most deprived MSOAs in the rest of England (beta = 0.136, $p < 0.01$).

After accounting for the age and ethnicity structure of MSOAs, deprived MSOAs in the North still have higher average COVID-19 mortality than in the rest of England (Fig. 3). The most deprived MSOAs in the North had a conditional mean of 26.01 deaths per 10,000 (95% C.I.: 24.60 to 27.42) compared to 22.98 deaths per 10,000 (95% C.I.: 21.80 to 24.16) in deprived MSOAs in the rest of England.

To test for the existence of spatial correlation in the regression residual from the simple linear model (Equation (1), column 4 of Table 3), we implemented the Stata command to calculate Moran's I. Under the null-hypothesis, there is no spatial correlation in the residuals/error

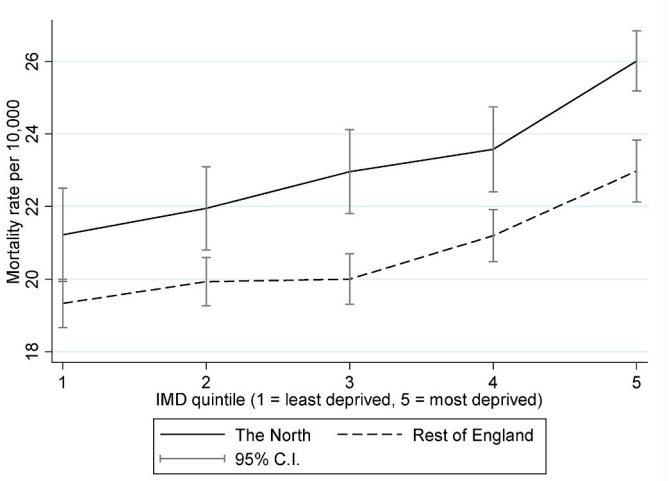

Fig. 2. Crude COVID-19 mortality rate by IMD quintiles: North vs. the rest of England.
Notes: The mortality rate is the population-weighted average of each MSOA within that part of England within that IMD quintile. Each MSOA's mortality rate is defined as the total number of deaths between March 2020 and April 2021 divided by the population estimate from 2019, expressed per-10,000 population. The mortality rates are not age-standardised. In addition, they are 14-month totals, not annual approximations. The 95% confidence interval is calculated by applying the formula mean ± 1.96 × s.e, where s.e. is the standard error of the mean.

Table 2
Crude COVID-19 mortality rate by IMD quintiles: North vs. the rest of England.

	Mean rate	95% CI
The North		
5 (most deprived)	26.01	25.18 to 26.84
4	23.58	22.40 to 24.75
3	22.96	21.81 to 24.12
2	21.95	20.80 to 23.10
1 (least deprived)	21.22	19.93 to 22.51
Rest of England		
5 (most deprived)	22.98	22.13 to 23.83
4	21.20	20.48 to 21.91
3	20.00	19.31 to 20.70
2	19.93	19.27 to 20.60
1 (least deprived)	19.33	18.67 to 20.00

Notes: The mortality rate is the population-weighted average of each MSOA within that part of England within that IMD quintile. Each MSOA's mortality rate is defined as the total number of deaths between March 2020 and April 2021 divided by the population estimate from 2019, expressed per-10,000 population. The mortality rates are not age-standardised. In addition, they are 14-month *totals, not annual approximations.* The 95% confidence interval is calculated by applying the formula mean ± 1.96 × s.e, where s.e. is the standard error of the mean.

terms the test statistic is distributed as $\chi^2(1)$. The test statistic is 1302.60 (p<<0.001). Hence, Moran's I strongly rejects the null-hypothesis of homoscedastic error terms and strongly indicates that there is substantial spatial correlation in the error terms, indicating the spatial model is preferred.

Figures C.1 and C.2 (in Appendix C) show maps of IMD quintiles and COVID-19 mortality rates, respectively. These provide further graphical evidence that (i) deprivation and higher mortality rates are more concentrated in the North and (ii) there are strong spatial clusters, where 'hot spots' of high deprivation and high mortality rates are geographically clustered.

Table 4 reports the coefficients from the model that explicitly allows for the spatial lag terms (Equation (2)). Here, we present both the estimated coefficient as well as the average direct effect, the average indirect effect, and the average total effect (see Appendix A).

The full spatial model confirms that MSOAs in the North were more likely to have higher COVID-19 mortality rates, and the size of the difference is larger than that reported in the linear model (column (4) of Table 3). Here, the North experienced 49.5% more deaths than the rest of the country (beta = 0.402; p < 0.001). There again exists a monotonic relationship in the coefficients of deprivation. However, when we break this down into average direct and average indirect effects, it appears that this is being driven by the average direct effect, especially for MSOAs in quintiles 2 and 3. However, there is strong evidence of both direct and indirect effects in the most deprived quintile. In the most deprived quintile (relative to the least deprived), the direct effect is an additional 40.6% deaths per-10,000 (beta = 0.341, p < 0.001) and the indirect effect is an additional 8.8% more deaths per-10,000 (beta = 0.084, p = 0.056), resulting in an overall total effect of 52.9% more deaths per 10,000 (beta = 0.425, p < 0.001).

The spatial lags on the dependent variable and the error term are strongly statistically significant adding further justification to the use of spatial models. The spatial lags on the IMD terms are not interpretable in their current form, and hence we compare direct and indirect effects (see above and Appendix A). The spatial lag on the outcome (beta = 0.070, p < 0.001) indicates that one additional death per 10,000 population in a neighbouring areas leads to 7.3% higher mortality rate in the area under consideration.

4. Discussion

We found strong evidence of the unequal effects of the pandemic. On average, regions in the North of England were much more likely to have higher COVID-19 mortality rates. We also showed that more deprived areas were considerably likely to have higher mortality than less deprived areas. Crucially, we have found that there were regional differences in the effects of deprivation. On average, deprived areas in the North fared worse than equally deprived areas in the rest of England. Our results also show that the higher COVID-19 mortality rates in the North persisted after adjusting for other possible confounding factors (age, urbanity and ethnicity). There was strong evidence of spatial clusters of increased mortality, and hence models that could account for this were preferred. The COVID-19 mortality rate of neighbouring areas had an effect on the mortality in each surrounding area, as did the level of deprivation in neighbouring areas. Given that deprivation is more prevalent in the North, this could in part explain the higher COVID-19 mortality rates there.

This is the first application of the deprivation amplification concept to the COVID-19 pandemic and our results suggest that there is potentially a deprivation amplification effect in regards to geographical inequalities in COVID-19 mortality rates. This takes two forms: firstly, deprived areas in the more deprived Northern regions had higher mortality rates than equally deprived areas in the less deprived regions in the rest of England; and secondly, some of the excess COVID-19 deaths in deprived areas in the North are associated with the deprivation rates of neighbouring areas. Together, this suggests empirically that it is not just the immediate neighbourhood context that matters for population health outcomes but also the wider regional and neighbouring contexts. This is a key aspect of deprivation amplification theory and so our results support the further use of this concept in geographical research.

As noted in the introduction, the broader relationship between deprivation and COVID-19 mortality has been previously explained through the syndemic pandemic concept (Bambra et al., 2020a; Bambra et al., 2021b). This has suggested that deprivation results in multiple, interacting and additive adverse risk factors for COVID-19 mortality (Bambra et al., 2020b), *acting through five pathways (*unequal exposure; unequal transmission; unequal vulnerability; unequal susceptibility; and unequal treatment) (Bambra et al., 2020a; Bambra et al., 2021b; Todd and Bambra, 2021; McGowan and Bambra, 2022). Our results suggest that the deprivation amplification concept can also be added to our

Table 3
The effect of region (North) and deprivation on COVID-19 mortality rates (unadjusted and adjusted).

	(1)	(2)	(3)	(4)
	Outcome: natural logarithm of COVID-19 mortality rates per 10,000; March 2020 to April 2021			
	b (95% CI)	b (95% CI)	b (95% CI)	b (95% CI)
MSOA is in the North	0.198***	0.396***	0.296***	0.208***
	(0.166–0.229)	(0.343–0.449)	(0.197–0.395)	(0.095–0.320)
Age categories included [a]		(0.221–0.354)	(0.260–0.390)	(0.294–0.422)
% of population who are white (reference category)				
% of the population who are multiple/mixed ethnic groups		0.025**	−0.010	−0.016
% of the population who are Asian/British Asian		(0.008–0.041)	(-0.027 to 0.007)	(-0.033 to 0.001)
		0.010***	0.009***	0.011***
		(0.008–0.012)	(0.007–0.010)	(0.009–0.012)
% of the population who are Black/African/Caribbean/Black British		0.007***	0.008***	0.007***
% of the population who are other ethnicities		(0.003–0.011)	(0.005–0.012)	(0.004–0.011)
		−0.006	−0.012	−0.010
		(-0.018 to 0.007)	(-0.024 to 0.001)	(-0.022 to 0.002)
% of the population who are multiple/mixed ethnic groups interacted with living in the North		−0.048*	−0.042*	−0.041
% of the population who are Asian/British Asian interacted with living in the North		(-0.088 to	(-0.083 to	(-0.082 to 0.000)
		−0.008)	−0.000)	
		−0.007***	−0.005***	−0.006***
		(-0.009 to	(-0.008 to	(-0.008 to
		−0.004)	−0.002)	−0.003)
% of the population who are Black/African/Caribbean/Black British interacted with living in the North		0.004	0.008	0.004
% of the population who are other ethnicities interacted with living in the North		(-0.012 to 0.020)	(-0.008 to 0.024)	(-0.012 to 0.020)
		−0.013	−0.004	0.010
Rural town and fringe (reference category)		(-0.047 to 0.020)	(-0.037 to 0.029)	(-0.022 to 0.043)
Rural village and dispersed			−0.236***	−0.271***
Urban city and town			(-0.306 to	(-0.341 to
			−0.166)	−0.202)
			0.109***	0.100***
			(0.052–0.166)	(0.044–0.157)
Urban major conurbation			0.329***	0.319***
Urban minor conurbation			(0.259–0.398)	(0.250–0.387)
			0.405***	0.356***
			(0.286–0.524)	(0.239–0.474)
Rural village and dispersed interacted with being in the North			−0.037	0.024
Urban city and town interacted with being in the North			(-0.186 to 0.113)	(-0.124 to 0.172)
			0.032	−0.001
			(-0.075 to 0.139)	(-0.107 to 0.105)
Urban major conurbation interacted with being in the North			−0.100	−0.159**
Urban minor conurbation interacted with being in the North			(-0.216 to 0.016)	(-0.274 to
				−0.044)
			−0.190*	−0.216*
			(-0.360 to	(-0.383 to
			−0.021)	−0.048)
IMD quintile 1 (least deprived; reference)				
IMD quintile 2				0.127***
				(0.082–0.172)
IMD quintile 3				0.143***
				(0.096–0.190)
IMD quintile 4				0.257***
				(0.205–0.309)
IMD quintile 5 (most deprived)				0.365***
				(0.301–0.429)
IMD quintile 2 interacted with being in the North				−0.000
				(-0.097 to 0.097)
IMD quintile 3 interacted with being in the North				0.083
				(-0.014 to 0.180)
IMD quintile 4 interacted with being in the North				0.031
				(-0.064 to 0.127)
IMD quintile 5 (most deprived) interacted with being in the North				0.136**
				(0.039–0.233)
Observations	6778	6778	6778	6778

95% confidence intervals in parentheses. *p < 0.05; **p < 0.01; ***p < 0.001.
Notes: [a] The additional variables relate to the percentage of the MSOA population in pre-specified age bands (see Table 1).

theory toolbox for understanding deprivation and COVID-19. It suggests that these syndemic pathways can be exacerbated in areas of higher deprivation if they are embedded within a wider context of local and regional deprivation.

This is the first application of the amplification deprivation concept to examine the influence of different geographical scales of deprivation on health. Previous use of the concept has focused on the influence of local area deprivation on the relationship between individual-level SES (such as individual or household income) and health outcomes. As such, our results have implications – not just for how we understand

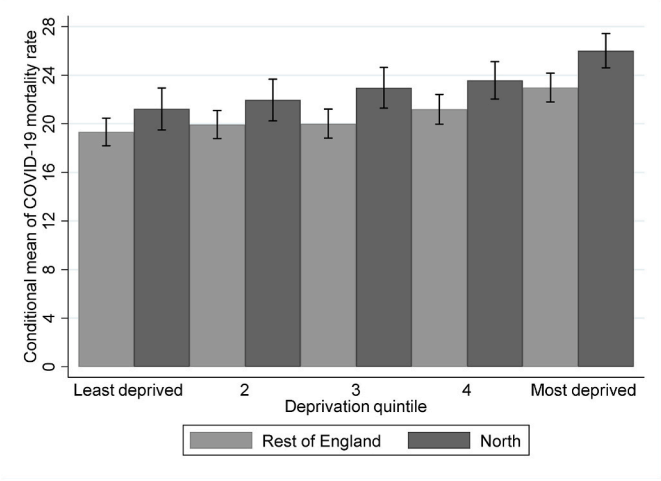

Fig. 3. Conditional COVID-19 mortality rate by IMD quintiles: North vs. the rest of England.
The conditional means are estimated using the regression output in Table 3, column (4) and accounts for the age and ethnicity composition of each MSOA as well as urbanity and deprivation including interactions with the North. The vertical lines are 95% confidence intervals obtained in the traditional way.

geographical inequalities in COVID-19 and the relationship between deprivation and mortality - but also for how we assess the value of the deprivation amplification concept within the broader health geography literature. In keeping with previous theoretical work (Bambra et al., 2019), our empirical results here suggest that issues of scale needed to be embedded into our understanding of what constitutes contextual influences on health. Specifically, our work suggests that the deprivation amplification concept can be expanded for wider analytical use within health geography. It has utility beyond just examining the interaction of individuals and local areas, to assessing the interaction of different spatial scales of deprivation on the health outcomes of local places. Our study thereby adds to the wider health geography literature debates on the relationship between health and place by suggesting that it is not just the immediate neighbourhood that constitutes contextual influences on population health but the wider regional and neighbouring local context (Cummins et al., 2007; Bambra et al., 2019).

Our results show that it is not only the level of deprivation in the specific area (MSOA) that is important for explaining that area's COVID-19 mortality, but also the levels of deprivation in neighbouring areas. It is therefore important to use statistical models that explicitly allow these spatial spill over effects to be modelled and quantified. As well as indirect effects operating through the deprivation of neighbouring areas, there were strong direct effects. Given the highly infectious nature of COVID-19, it is important to allow for the outcomes of geographically proximal areas to have effects on the outcomes of the areas they border.

4.1. Strengths and limitations

Our analyses use information on all MSOAs within England, and hence has national coverage. We were able to merge in information on important factors that have been shown to be strongly predictive of COVID-19 outcomes (age and ethnicity). Additionally, we were able to assess the deprivation amplification hypothesis by obtaining detailed information on the relative position of each MSOA nationally and assigning to quintiles. The statistical models used allowed us to account for and quantify direct and indirect effects between neighbouring areas. Our study also used a theory-guided approach. However, our study is subject to some important limitations. Firstly, using COVID-19-specific mortality, as opposed to a measure of excess mortality, could have biased – underestimated – our estimates of the effect of area deprivation

Table 4
The effect of region (North) and deprivation on COVID-19 mortality rates (unadjusted and adjusted) when accounting for spatial clusterings and spillovers.

	Spatial model; Equation 2
MSOA is in the North	0.402*** (0.273–0.532)
IMD quintile 1 (least deprived; reference)	Reference
IMD quintile 2	0.103*** (0.062–0.144)
Average direct effect [b]	0.100*** (0.063–0.137)
Average indirect effect [b]	−0.062 (−0.153 to 0.029)
Average total effect [b]	0.038 (−0.068 to 0.144)
IMD quintile 3	0.125*** (0.081–0.169)
Average direct effect [b]	0.139*** (0.0995–0.179)
Average indirect effect [b]	−0.023 (−0.110 to 0.064)
Average total effect [b]	0.116* (0.018–0.214)
IMD quintile 4	0.221*** (0.171–0.272)
Average direct effect [b]	0.225*** (0.181–0.270)
Average indirect effect [b]	0.002 (−0.085 to 0.089)
Average total effect [b]	0.227*** (0.130–0.325)
IMD quintile 5 (most deprived)	0.307*** (0.243–0.370)
Average direct effect [b]	0.341*** (0.287–0.396)
Average indirect effect [b]	0.084 (−0.002 to 0.169)
Average total effect [b]	0.425*** (0.329–0.522)
IMD quintile 2 interacted with North [c]	−0.009 (−0.097 to 0.080)
IMD quintile 3 interacted with North [c]	0.050 (−0.041 to 0.141)
IMD quintile 4 interacted with North [c]	0.013 (−0.079 to 0.106)
IMD quintile 5 interacted with North [c]	0.118* (0.019–0.217)
MSOA age and ethnicity profiles and urbanicity included [a]	Yes
Outcome (ρ)	0.070*** (0.043–0.098))
Error Term (ε)	0.601*** (0.561–0.641)
IMD terms [d]	Included
Observations	6791

95% confidence intervals in parentheses. *p < 0.05; **p < 0.01; ***p < 0.001.
Notes: [a] The additional variables relate to the percentage of the MSOA population in pre-specified age bands and the percentage of the MSOA population classified into five broad ethnicity groups as well as five categories or urbanicity (see Table 1). [b] The definition of average effect (direct, indirect and total) for the spatial model is provided in Appendix A. [c]: We cannot compute the direct, indirect, and total effect here as some MSOAs are on the boundary of the North and hence some neighbouring MSOAs are in the North and some are in the rest of England. In this case, they parameters cannot be estimated. [d]: we also include spatial lags of the key IMD terms, as well as their interaction with North, but we omit them here for reasons of brevity. They are all statistically insignificant at p < 0.05.

on deaths. Secondly, we used mortality data from MSOAs in England. This was because this was the smallest spatial scale data that was publicly available for COVID-19 mortality rates when we conducted our analyses. However, analysis of smaller-level geographies (such as Lower Super Output Aras – LSOAs) would allow a more precise estimation of the extent of area-level inequalities in COVID-19 mortality. The regional focus of our analysis also has limitations as, for example, the North is less ethnically diverse than the rest of England, on average. Although this does not apply to certain parts of the North such as Greater Manchester – which is more diverse, or in contrast, parts of the South such as Cornwall which are less ethnically diverse. Further, our analysis examines the whole 14-month period for which COVID-19 mortality data by MSOA is available. We have not thereby examined any temporal differences by region that may have occurred during the different phases of the pandemic (e.g. by wave) (Griffith et al., 2021). Finally, whilst we have identified relationships at the area level we cannot, of course, assume that our findings hold true at the individual level. To do so would be to risk the ecological fallacy since relationships identified for areas cannot be assumed to apply to individuals (Fieldhouse and Tye, 1996).

5. Conclusion

This study has used the concept of 'deprivation amplification' to explore the relationship between deprivation, scale and COVID-19 mortality rates. We found that the more deprived Northern regions and the more deprived MSOAs across the country had higher COVID-19 mortality rates. We also found that the most deprived MSOAs in the more deprived Northern regions suffered even greater COVID-19 mortality rates. We also found strong evidence of spatial clustering and spillovers. We argue that this is evidence of deprivation amplification within the COVID-19 pandemic. Our findings reinforce discussions on the syndemic nature of inequalities in the COVID-19 pandemic whilst also advancing the health and place literature by suggesting that the deprivation amplification concept has wider utility in the health geography literature than has previously been explored.

Data availability

The authors do not have permission to share data.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.healthplace.2022.102933.

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