Area deprivation and COVID-19 incidence and mortality in Bavaria, Germany: a Bayesian geographical analysis

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Research Article

Keywords: COVID-19, standardised incidence ratio, standardised mortality ratio, area deprivation, Bavarian Index of Multiple Deprivation, hierarchical models

Posted Date: April 15th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1561504/v1

Abstract

Background

Area deprivation has been shown to be associated with various adverse health outcomes including communicable as well as non-communicable diseases. Our objective was to assess potential associations between area deprivation and COVID-19 standardised incidence and mortality ratios in Bavaria over a period of nearly two years. Bavaria is the federal state with the highest infection dynamics in Germany.

Methods

In this retrospective, observational ecological study, we estimated the strength of associations between area deprivation and standardised COVID-19 incidence and mortality ratios (SIR and SMR) in Bavaria, Germany. We used official SARS-CoV-2 reporting data aggregated in monthly periods between March 2020 and December 2021. We employed unstructured random effects models to study global trends and the Besag-York-Mollie (BYM) model to account additionally for neighbourhood structures. Area deprivation was assessed using the quintiles of the 2015 version of the Bavarian Index of Multiple Deprivation (BIMD 2015) at district level, analysing the overall index as well as its single domains.

Results

SIRs and SMRs were higher in more deprived than in less deprived districts. Aggregated over the whole period, the SIR increased by 1.04 (95% confidence interval (95% CI): 1.01 to 1.07, $p = 0.002$), and the SMR by 1.11 (95% CI: 1.07 to 1.16, $p < 0.001$) per BIMD quintile. Looking at individual months revealed clear linear association between the BIMD quintiles and the SIR and SMR in the first, second and last quarter of 2021. During the summer periods in 2020 and 2021 no effect could be assessed. Effects were also observed for the domains income, employment, and social capital deprivation.

Conclusions

In more deprived areas in Bavaria, Germany, higher incidence and mortality ratios were observed during the COVID-19 pandemic with particularly strong associations during infection waves 3 and 4 in 2020/2021. Only high infection levels reveal the effect of causal risk factors and socioeconomic inequalities. There may be confounding between the high BIMD and border regions in the north and east of Bavaria, making the relationship between area deprivation and infection burden more complex.

Background

Deprived areas facing a lack of material and social resources are often associated with worse health outcomes compared to areas being relatively better off [1]. More specifically, area deprivation relates to a large number of adverse health outcomes, e.g. coronary heart disease, type 2 diabetes or cancer [2, 3, 4, 5]. To analyse those area-level health disparities, deprivation indices are widely used [6, 7, 8].

The association between aspects of the Coronavirus disease 2019 (COVID-19) and area deprivation has been investigated for several countries including Germany, on which our study is focusing [9, 10, 11, 12, 13, 14, 15, 16, 17]. The studies consistently report that the risk of COVID-19 infections as well as COVID-19-related mortality is higher in more deprived than in less deprived areas. However, it was also observed that this relationship could change over time [18, 19].

Furthermore, deprivation indices contain several distinct domains to describe area-based lack of material and social resources. Typically, income and employment are key domains of deprivation indices but also other indicators, e. g. education or environmental aspects.

Hence, with respect to COVID-19 it should be of interest to include data of longer time periods in order to consider time variations and to disentangle associations of different deprivation domains with COVID-19 incidence and mortality.

By generating corresponding evidence, the present work intends to contribute to potential policy measures, by providing transparent and objective information to quantify regional social inequalities and their relationship to health. In German media and the public, aspects of regional deprivation were often discussed with respect to vaccination activities or intensive care infrastructure during the COVID-19 pandemic. However, the measurement of deprivation did not follow a consistent approach.

The very first SARS-CoV-2 outbreak in Germany was reported for the southern federal state of Bavaria [20, 21], which is the largest and by population size the second largest federal state of Germany with more than 13 million inhabitants. Since March 2020, several infection waves have occurred and by submission of this paper, Bavaria and Germany are in the transition between the fifth and sixth infection wave. To date, Bavaria still lacks a comprehensive analysis on how area deprivation and the COVID-19 burden relate to each other over the course of the pandemic.

Therefore, the specific aim of our study is to investigate the association between area deprivation and standardised SARS-CoV-2 incidence and mortality ratios (SIR, SMR) between spring 2020 and winter 2021 at the district level in Bavaria, Germany, and to assess whether area deprivation at specific time points and over longer periods consistently explains the variability in local population-adjusted COVID-19 incidence and mortality.

Methods

Data source and structure

The Bavarian Health and Food Safety Authority (*Bayerisches Landesamt für Gesundheit und Lebensmittelsicherheit*, LGL) is the competent authority in Bavaria for SARS-CoV-2 reporting by publishing aggregated data of all local Bavarian health offices [22]. We prepared the data provided by the LGL for 2020 and 2021, beginning March 1, 2020, through December 31, 2021, thus excluding sporadic infections prior to March 2020. This period includes data from the first to the fourth wave of infection [23]: the first wave started in calendar week 10 in 2020 (02/03/2020) in Germany and lasted until 17/05/2020, followed by a summer plateau in 2020 between 18/05/2020 and 27/09/2020. The second wave started on 28/09/2020 and lasted until 28/02/2021. The third wave started on 01/03/2021 and went on until 13/06/2021, followed by a summer plateau in 2021 (between 14/06/2021 and 01/08/2021). The fourth wave started on 02/08/2021 and continued until 26/12/2021 [23].

In Germany, incident cases are persons with laboratory-confirmed evidence of SARS-CoV-2 (direct pathogen detection). COVID-19 deaths additionally need to have died in relation to this infection [24]. In practice, it is often difficult to decide to what extent the SARS-CoV-2 infection directly contributed to the death. Both groups, people who died directly from the disease (“death due to COVID-19”) as well as patients with pre-existing conditions who were infected with SARS-CoV-2 and for whom it cannot be conclusively established what the cause of death was (“death with COVID-19”), are reported as COVID-19-related deaths.

Area deprivation

Area deprivation was assessed by the Bavarian Index of Multiple Deprivation (BIMD) for the reference year 2015 (BIMD 2015) on the district level (“Kreisebene”) [25]. Bavaria consists of 96 rural and urban administrative districts. The BIMD as well as the area deprivation measure for the whole of Germany, the German Index of Multiple Deprivation (GIMD), have been established based on the method used in the UK and adapted to the German context [6]. Both indices have been shown to be associated with a number of adverse health outcomes in non-communicable diseases, including diabetes and cancer incidence, but also mortality [26, 27, 28].

The BIMD consists of seven deprivation domains with different weighting: income (25%), employment (25%), education (15%), municipal/district revenue (15%), social capital (10%), environment (5%), and security (5%) [25, 26]. In our analysis, we used quintiles of the overall score and the domain-specific scores ("deprivation quintiles") where quintile 1 (Q1) includes the least deprived and quintile 5 (Q5) the most deprived districts. We label the quintiles as follows: least deprived (Q1), less deprived (Q2), moderately deprived (Q3), more deprived (Q4), and most deprived (Q5). During the observation period, we assigned to each district a constant deprivation quintile not changing over time.

Statistical analyses

We determined SIR and SMR as ratios of observed to expected infection incidence and mortality rates. We calculated the expected values using indirect standardisation to the latest available Bavarian population (from 2020) [29]. For this approach, the population was stratified into 15 age and sex-specific categories (0–4, 5–9, ..., 60–64, 65–74, and 75 years and older). For each month, the stratum-specific event rates (infection/mortality) for the whole of Bavaria were multiplied by the specific population of the district. Summing over all strata gives the local expected number of events. The locally observed numbers of events were divided by the locally expected number to get the local standardised event ratio. These ratios can therefore change every month. Monthly, they represent the extent of heterogeneity in both epidemic measures across the Bavarian population. Premature mortality was defined as mortality in SARS-CoV-2 patients aged < 65 years. All individuals without valid age and/or sex information were excluded (n = 10,993, 0.8% of data).

The primary analysis studied the association of area deprivation with SIR and SMR simultaneously by using the bivariate version of the Besag-York-Mollie (BYM) model [30, 31, 32]. This model has been referred to as a standard model in geographical epidemiology [33]. The BYM model incorporates both rates as a bivariate endpoint and takes the correlation between them into account. This is a common strategy to increase the power of detecting specific associations [34]. The model also takes into account that the relative risks of neighbouring regions are correlated and introduces smoothing of extremely large estimates, which are generally caused by few observations in small regional populations. As is often the case, only nearest neighbours (i.e. districts with a common border) are considered for the correlation in the model, whereas next nearest neighbours are not. Border effects are neglected, i.e. morbidity and mortality in neighbouring districts outside Bavaria are not taken into account. Neighbouring German federal states of Bavaria are Baden-Wuerttemberg and Hesse in the west, and Thuringia and Saxony in the north. Neighbouring countries are the Czech Republic in the east, Austria in the east and the south, and Switzerland in the south of Bavaria. The deprivation quintiles were included in the BYM model as an ordinal variable. A test for linear trend used a linear contrast for the quintiles centred on their mean (-2, -1, 0, 1, 2).

The BYM model uses non-informative a priori distributions according to the default settings of the analysis software [35]. We reported the mean estimates averaging over 100,000 replications, including an initial burn-in period of 10,000. Point estimates were reported together with 95% credibility intervals (95% CrI). Statistical significance is claimed if the 95% CrI does not contain the value zero. These models are referred to as structured models.

To assess a marginal effect of the BIMD 2015 on the SIR and the SMR over the entire observation period, multilevel models were used with district and time as random effects and BIMD or any of the seven domains as fixed effects. These models are referred to as non-structured models. Hierarchical tests for statistical significance were conducted as follows: First, the main effect of the association between BIMD and SIR/SMR was estimated, and statistical significance was claimed at a 5% confidence level. If the main effect was found to be statistically significant, analyses were conducted for the seven domains. The p-values for the domains were adjusted using the Bonferroni correction. Point estimates are reported together with 95% confidence intervals (95% CI).

The non-structured models were estimated using the R function "glmer" [36]. The R function "supsmu" was used to smooth daily incidence and mortality rates to present smoother curves [37]. The analyses were carried out using the software R (Version 3.6.3.) [38] and GeoBUGS (Version 1.2) [35]. Maps were generated in QGIS 3.10.10 [39].

Results

Overview

From March 1st, 2020 to December 31st, 2021 a total of 1,319,456 SARS-CoV-2 infections and 19,571 associated deaths have been reported in Bavaria, Germany. Among persons aged under 65 years, a total of 1694 COVID-19-associated deaths have been reported (8.5% of all deaths). Of the 96 districts, 19 (20, 18, 20, and 19) belong to the first (second, third, fourth, and fifth) BIMD quintile, respectively. The districts belonging to each BIMD quintile are shown in Figure 1 a). As can be seen from Additional File 1, the assignment of districts to BIMD quintiles looks different for each domain of the BIMD. In addition, Figures 1 b) and c) show maps of SIR and SMR of accumulated data over the whole observation period.

Unstructured analysis of overall area deprivation effects

The overall strength of the association between area deprivation, measured by either the BIMD 2015 or its single domains, and SIR/SMR was calculated for the entire study period while adjusting for district and time. The results are shown in Figure 2 for the BIMD 2015 and in Table 1 for the BIMD 2015 and its seven domains. For the BIMD 2015, a statistically significant positive association was found with SIR and SMR (SIR=1.04 (95% CI: 1.01 to 1.07), p=0.002; SMR=1.11 (95% CI: 1.07 to 1.16), p<0.001, per one quintile increase in the BIMD 2015). Hence, the SIR/SMR increases with increasing area deprivation.

Table 1: Strength of associations between area deprivation and standardised incidence and mortality ratios in Bavaria, Germany.

Area deprivation index / domain	**SIR**	**95% CI SIR**	**p**	**SMR**	**95% CI SMR**	**p**
BIMD 2015	**1.04**	**(1.01, 1.07)**	**0.002**	**1.11**	**(1.07, 1.16)**	**<0.001**
Income	**1.05**	**(1.02, 1.08)**	**0.003**	**1.11**	**(1.06, 1.16)**	**<0.001**
Employment	1.02	(1.00, 1.05)	0.653	**1.09**	**(1.05, 1.14)**	**<0.001**
Education	1.03	(1.00, 1.06)	0.155	1.06	(1.01, 1.11)	0.068
Municipal/district revenue	1.01	(0.99, 1.04)	1	1.05	(1.00, 1.10)	0.421
Social capital	**1.04**	**(1.02, 1.07)**	**0.010**	**1.11**	**(1.06, 1.16)**	**<0.001**
Environment	**0.95**	**(0.93, 0.98)**	**0.005**	1.00	(0.95, 1.04)	1
Security	1.02	(1.00, 1.05)	0.693	0.99	(0.95, 1.04)	1

SIR = standardised incidence ratio, CI = confidence interval, SMR = standardised mortality ratio. Ratios were calculated accumulating the data between 01/03/2020 and 31/12/2021 and adjusted for district and time. Statistically significant results are printed in bold. P values for the Bavarian Index of Multiple Deprivation 2015 (BIMD 2015) domains are Bonferroni adjusted for multiple testing. A p-value after adjustment of >1 is coded as 1.

With respect to the single domains, statistically significant positive associations were found for SIR and SMR with income deprivation (SIR=1.05 (95% CI: 1.02 to 1.08), p=0.003; SMR=1.11 (95% CI: 1. 06 to 1.16), p<0.001 per one quintile increase) and social capital deprivation (SIR=1.04 (95% CI: 1.02 to 1.07), p=0.010; SMR=1.11 (95% CI: 1.06 to 1.16), p<0.001 per one quintile increase). Another positive association was found for SMR with employment deprivation (SMR=1.09 (95% CI: 1.05 to

1.14), p<0.001 per one quintile increase) and a negative association for SIR with environmental deprivation (SIR=0.95 (95% CI: 0.93 to 0.98), p=0.005).

Unstructured analysis of time-specific area deprivation effects

Figure 3 displays the daily reported incidence as well as overall and premature SARS-CoV-2-associated mortality rates over districts belonging to each BIMD 2015 quintile. To indicate the first wave, the graph starts in January 2020 and covers the entire time period until December 2021. Hence, the incidence rate (IR) curve (Figure 3a) qualitatively shows the four pandemic waves in Bavaria. The time periods of the waves according to the official definition [23] are shown as light grey-shaded areas in the figure 3.

During the first wave in March/April 2020, the least and more deprived districts (Q1 -black and Q4 -brown) have the highest IR, whereas the most deprived districts have the lowest rates (Q5 -green). At the beginning of the second wave in August 2020, moderately deprived districts (Q3 -blue) show the highest IR, but later during the wave, the most deprived districts are the most affected ones peaking in October and November 2020. Around Christmas 2020, the districts in Q4 and Q5 show an increase in IR, and these two categories remain the ones with the highest IR until the end of the third wave. At the beginning of the fourth wave in August 2021, districts in Q1 and Q3 show higher rates. After the rapid increase in pandemic activity in September and October 2021, again districts in Q4 and Q5 have the highest IR.

In terms of mortality rates (MR, Figure 2b), MR generally peak a few weeks after the peak in IR. During the first wave, MRs are highest in the districts Q4 and Q1, similar to IRs. The second MR peak is observed around Christmas 2020, with MR highest in Q4 and Q5 districts, which is also true for the third and fourth pandemic waves. Premature mortality (Figure 2c) shows a similar ranking of districts as mortality rates. However, because of the smaller sample size, the curves are not as smooth. In the second and in the third wave, the least deprived districts in Q1 show a nearly constant and very low MR. It is interesting to note that while overall COVID-19 mortality rates decline after the second wave, the magnitude of premature mortality remains about the same.

Structured analysis of time-specific area deprivation effects

Figure 4 shows the estimates of the BYM model for the bivariate endpoint SIR and SMR over time for each quintile of the BIMD 2015. BYM models take into account unstructured as well as neighbourhood-specific random effects (convolution model) and allow for multivariate endpoints. The data were aggregated in monthly periods. The point estimate for each quintile is shown along with the 95% credibility interval, and the value of one ("no effect") is shown as a dashed line.

At the beginning of the first wave in March 2020, the SIR and SMR are higher in the least deprived districts. However, as the first wave continues this effect disappears. Between the first and the second wave in summer 2020, infection and death counts were low, which is reflected in wide credibility intervals. At the beginning of the second wave, districts from the two least deprived quintiles (Q1 and Q2) appear to have a slightly lower SIR. However, taking into account the uncertainty of the estimates, no clear conclusion can be drawn from this. In December 2020, in the middle of the second wave, the trend of an increasing SIR with increasing area deprivation becomes statistically significant and remains so until the end of the third wave. The fourth wave begins with the same significant trend of higher incidence ratios in more deprived districts, and by the end of the fourth wave, the effect is still present.

Mortality ratios show similar trends compared to incidence rates, but with a certain time lag. In the last month (December 2021), the SIR was 0.92 (95% CrI: 0.78 to 1.07) for the least deprived and 1.13 (95% CrI: 0.94 to 1.32) for the most deprived districts. The corresponding numbers for SMR are 0.81 (95% CrI: 0.60 to 1.03) and 1.33 (95% CrI: 0.96, 1.72). Figure 4 also implies that the association between the BIMD 2015 and SIR/SMR is strongly fluctuating over time (tests on time x BIMD interaction are highly significant with $p<0.00001$).

Corresponding analyses for the seven domains of the BIMD 2015 are shown in Additional files 2 to 8. During the first wave, no clear association between income deprivation and SIR/SMR can be observed (Additional file 2). In the second and third waves, higher SIRs and SMRs are detected in districts with higher income deprivation. At the end of the fourth wave, this effect is also present for both SIR and SMR.

From the second wave onwards, the SIR showed higher values in districts with higher employment deprivation (Additional file 3), which occasionally also applies for the SMR. Between these waves, the association shows no clear direction.

Education deprivation (Additional file 4) shows a significantly positive linear trend with SIR and SMR, starting in the second wave and continuing until the fourth wave. It appears that the association is significant either at the beginning and/or at the end of the waves.

A negative linear trend between municipal/district revenue deprivation and SIR (Additional file 5) can be seen for the times between the waves, implying that infection ratios are higher in districts with lower municipal/district revenue deprivation. During the waves, SIR is occasionally both positively and negatively associated with SIR and SMR.

Social capital deprivation (Additional File 6) is associated with SIR/SMR at the end of the second wave (SIR) or in the third wave (SMR), where higher deprivation is associated with higher SIR/SMR. This association is also evident in the fourth wave.

Environmental deprivation (Additional file 7) shows a positive and significant linear trend with SIR mostly between waves where only small numbers of cases occur. A similar observation holds between the third and fourth wave for SMR. In the fourth wave, the positive linear trend in SIR/SMR changes to a negative linear trend, indicating higher SIR and SMR in less deprived districts.

Security deprivation (Additional file 8) shows hardly any relevant association with SIR/SMR.

Discussion

This study investigated the association between area deprivation and regional SARS-CoV-2-associated incidence and mortality ratios by districts in Bavaria from the first until the fourth pandemic wave between March 2020 and December 2021. Besides the general view on area deprivation, we also studied the relevance of specific domains on COVID-19-related epidemiological outcomes. Bavaria is a large German state with over 13 million inhabitants and high infection activity during the COVID-19 pandemic. In addition to infection incidences, we examined whether the effects of area-based material and social deprivation were also reflected in mortality. The focus was laid to standardised ratios (standardised incidence or mortality ratio (SIR/SMR)) accounting for the demographic structure of the regions using a model, which accounts for the correlation between both measures (BYM model). We also used unstructured random effect models for time-aggregated analysis.

In the unstructured analysis (excluding regional structure and averaging over longer time periods), area deprivation, as measured by the well-established Bavarian Index of Multiple Deprivation, showed a positive association with SIR/SMR, implying that the COVID-19 burden increases with increasing area deprivation. With respect to the seven area deprivation domains included in the BIMD 2015, income and social capital deprivation were shown to be positively associated with incidence and mortality ratios. Additionally, employment deprivation and SMR were found to be positively associated, while the association between environment deprivation and SIR was negative. These observations are in accordance with a respective study for Belgium [18].

Our findings are in line with several previous results. The association of area deprivation and the health burden of COVID-19 has been studied in a number of international studies, e. g. from the United Kingdom [9, 40], India [10], Brazil [41], Italy [42], and the United States [11, 12, 43, 44]. The study by Bach-Mortensen *et al.* [9] investigated the association between area deprivation and COVID-19 outbreaks and related deaths among care home residents in England. Deaths were found to be more common in the most deprived compared to least deprived regions, whereas outbreaks in the care homes did not vary by area deprivation. Higher social deprivation, quantified using the Townsend Deprivation Score, was found to be associated with greater risk of dying from COVID-19 in another study from the United Kingdom [40]. Study results from India and the United States showed that higher SARS-CoV-2 incidences or odds of infection have been found in more deprived areas compared to less deprived areas [10, 11, 12]. Studies from Brazil and Italy concerning case-fatality ratio (CFR) and COVID-19 related deaths found a higher CFR and increased risk of death in people living in regions of highest deprivation [41, 42]. Comparing rural and urban environments in the United States, a study from Kitchen and colleagues found a positive relationship between area deprivation and COVID-19 prevalence, which was higher for rural counties, when compared to urban ones [43]. A combination of area level deprivation data and individual data from two U.S. municipalities was analysed in a study by Feehan *et al.* [44]. While higher area deprivation was found to be associated with higher risk of SARS-CoV-2 infection, the authors found that individual-level data accounted for a significant proportion of this association.

Interestingly, our results also show that during the first wave higher SIR and SMR were observed in less deprived districts, whereas this association reversed over time. This finding has also been confirmed in German-wide studies [13, 19]. The association between infection incidence and social deprivation during the first wave was investigated by Wachtler *et al.* and Plümper and Neumayer [13, 19]. For this purpose, the German Index of Socioeconomic Deprivation from the Robert Koch Institute, Germany's national Public Health institute, was linked to incidence data [13]. However, this index considers only three dimensions of deprivation, whereas the BIMD considers seven domains. Across Germany, higher incidences were observed in less deprived regions at the onset of the pandemic, which was associated with affluent ski vacationers returning with SARS-CoV-2 infection. Over time, this effect disappeared in the generally less deprived south of Germany (federal states of Baden-Württemberg and Bavaria), while higher incidences were observed in other more deprived regions. Similar observations were published by Pluemper and Neumayer [19], where the authors concluded that COVID-19 started as a rich man's disease and slowly transformed into a poor man's disease. Socioeconomic differences in infection risk during the second wave were investigated in Germany by Hoebel and colleagues [14]. Similar to the first wave, a higher incidence rate was found in less deprived regions at the beginning of the second wave. Again, this pattern reversed as the second wave progressed. In the second wave, COVID-19-related mortality and area deprivation were also examined in Germany, with higher mortality rates found among residents of deprived areas [15]. In the third wave of infection, higher incidences were observed in socioeconomically disadvantaged regions [16, 17], which was related to the fact that individuals from socioeconomically disadvantaged regions were not able to limit their mobility as much as individuals from less disadvantaged regions due to their occupation [16]. The fourth wave showed a similar association of infections and area deprivation as the second wave, despite the vaccination campaign [17]. It is worth mentioning that in our study the overall mortality during the third and fourth waves was reduced compared to the second wave, while no reduction in premature mortality (mortality within persons of an age below 65) was observed. This might be attributable to the vaccination campaign, which was launched on 27/12/2020 in Germany [45]. Similar to many other countries, older age groups and the most vulnerable persons were prioritised for the vaccination in Germany. A study by Wollschlaeger et al. [46] in the German federal state of Rhineland-Palatinate found an association between higher vaccination coverage and a decrease in COVID-19 fatalities in the 80 + age group in the first months of 2021, supporting our hypothesis. Another study with individual level vaccination data in Bavaria found a high vaccine efficacy in persons over 80 years of age over a similar observation period [47].

Possible reasons for the finding of increased infection rates with increasing area deprivation can be various. People in materially and socially advantaged areas might show stronger adherence to recommended behavioural changes during the pandemic [48, 49]. Such changes include contact reductions or better opportunities for remote working from home, which is still recommended in Germany in spring 2022. Regarding mortality, the underlying reasons are probably more complex. Potentially some of the outcomes could be related to different pre-existing health conditions (other than COVID-19) in the differently deprived areas. In Germany, COVID-19 mortality is often assessed only descriptively, and the underlying patterns have not yet been studied in depth. A study from Bavaria investigating the factors related to mortality from COVID-19 in persons over 50 years found SIR to have the greatest effect on the SMR [50].

The district-level BIMD, as used in our study, is defined for Bavarian districts with varying population sizes (from 40,842 to 1,488,202 inhabitants, median 117,648) and represent a relatively coarse resolution for the deprivation at hand. Individual districts may represent a complex mixture of different settings. However, when using the area-based index, it is assumed that the districts are homogeneous within themselves. Therefore, the BIMD 2015 at the district level as a proxy for individual socio-economic data has to be handled with care. A large number of disadvantaged households may account for a few cases, while a few rich households may account for a large amount of infections. In terms of aggregated data, the district may have both a high level of deprivation as well as high incidence rate, but in fact lower individual social deprivation is related to lower incidence. This may contain the risk of ecological bias arising from the assumption that inferences can be made about individual patterns based on patterns observed in clusters (groups). However, since the COVID-19 data in Germany are aggregated at the district level, this is the smallest spatial level we could choose. This limitation is common to all studies using data at an aggregated level.

To our knowledge, there is so far only one Germany-wide study that has investigated differences in the risk of SARS-CoV-2 infection according to socioeconomic position at the individual level [51]. Individual socio-economic position was measured by education and income. The study found significantly increased odds of SARS-CoV-2 infection among low-educated adults compared to highly educated adults. In terms of income, the odds of infection were higher for low-income than high-income individuals, even if the result was not statistically significant. The data were collected during the second infection wave. These results are consistent with our study on the dimensions of education and income deprivation. Nevertheless, our study shows that there are other additional factors, such as employment and social capital deprivation, that link deprivation to regional COVID-19 burden.

A limitation of this study may be potential confounding of area deprivation and geographic location. It could be that an area neighbouring Bavaria increases infection incidence in that Bavarian border district with high deprivation. Border districts may have higher BIMD 2015 values (see Fig. 1a). This would artificially strengthen the association between BIMD 2015 and SIR. The model used only considers the neighbourhood effect within Bavaria and neglects any effects outside the region. Additional file 1 shows the distribution of the quintiles of deprivation domains across the Bavarian districts. It is easy to see that the BIMD and some of its domains follow the geographical east and north-east trend. This is also true for domains such as income and social capital deprivation. However, education deprivation also shows a westward trend and is detected as an influential deprivation aspect in our structured analysis of time-specific area deprivation effects (see Additional file 4).

Despite neighbourhood effects coming from outside the region of interest, we followed the use of a modelling approach that takes into account the spatial structure of the data, such as the Besag-York-Mollie (BYM) model. Additionally, the bivariate version of the model, as used in the present study, further takes into account the correlation between both endpoints, which is relevant for the simultaneous modelling of SIR and SMR and makes the analysis of potential effects more powerful. It appeared that the unstructured model was also able to identify the main drivers of the relationship between area deprivation and incidence and mortality ratios.

We believe that another strength of our analysis lies in the combination of a longitudinal data perspective (covering almost the first two years of the pandemic) with a bivariate outcome that looks at SIR and SMR simultaneously. By including a bivariate outcome, the structured model accounted for the correlation between the two measures and the associations of SIR and SMR between neighbouring districts. In addition, we explored the different dimensions of deprivation that allowed us to see which domains might be affected differently by the pandemic. These findings are consistent with other studies, but additional dimensions of social capital deprivation and, to a lesser extent, environmental deprivation, were detected. It is also interesting to note that deprivation effects became effective when pandemic activity was high: when the crisis intensifies, aspects of social equity become even more important.

In the German media and public, regional aspects of deprivation related to vaccination activities or critical care infrastructure were frequently discussed. We believe that our work shows that the BIMD is an adequate instrument to measure deprivation in a consistent way. It provides reliable information for regional public health decision-making during the COVID-19 pandemic.

Conclusions

This study reports results of a retrospective ecological study investigating the relationship between area deprivation and SARS-CoV-2-related burden. Using a geographical analysis approach (correlation between neighbouring regions, correlation between the two endpoints of incidence and mortality), an association between area deprivation and COVID-19-specific standardised incidence and mortality ratios was found in Bavaria, Germany. Standardised incidence and mortality ratios were higher in more deprived than in less deprived districts. Income, employment, education and social capital were additionally identified as factors contributing to higher COVID-19 disease burden in districts with high levels of income, employment, education and social capital deprivation. Accompanying individual-level analyses are needed to understand the complex relationship between socio-economic characteristics and COVID-19 health outcomes. However, this study shows that the BIMD 2015 is suitable to identify regional differences in SARS-CoV-2 associated infection incidence and mortality in Bavaria.

Abbreviations

BIMD 2015 = Bavarian Index of Multiple Deprivation for the reference year 2015

BYM model = Besag-York-Mollie model

CI = confidence interval

CrI = credibility interval

CFR = case-fatality ratio

COVID-19 = Coronavirus disease 2019

LGL = Bayerisches Landesamt für Gesundheit und Lebensmittelsicherheit (Bavarian Health and Food Safety Authority)

SIR = standardised incidence ratio

SMR = standardised mortality ratio

Declarations

Ethics approval and consent to participate

This study was approved by the Ethics Committee of the Medical Faculty of the LMU Munich (Nr. 21-0213 KB).

Consent for publication

Not applicable

Availability of data and materials

The datasets generated and/or analysed during the current study are not publicly available due to confidentiality of the infected persons but are available in aggregated form from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

Funding

No funding was received for the study.

Authors' contributions

WM and LS designed the study. KMM, UM and WM acquired the data. WM and UM helped KMM with the methodology and KMM analysed the data. All authors interpreted the data. KMM and WM wrote the first draft of the manuscript. All authors read, revised and approved the final manuscript.

Acknowledgements

We would like to thank the team of Dr. Katharina Katz from the Bavarian Health and Food Safety Authority (LGL) for providing the SARS-CoV-2 reporting data.

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Figures

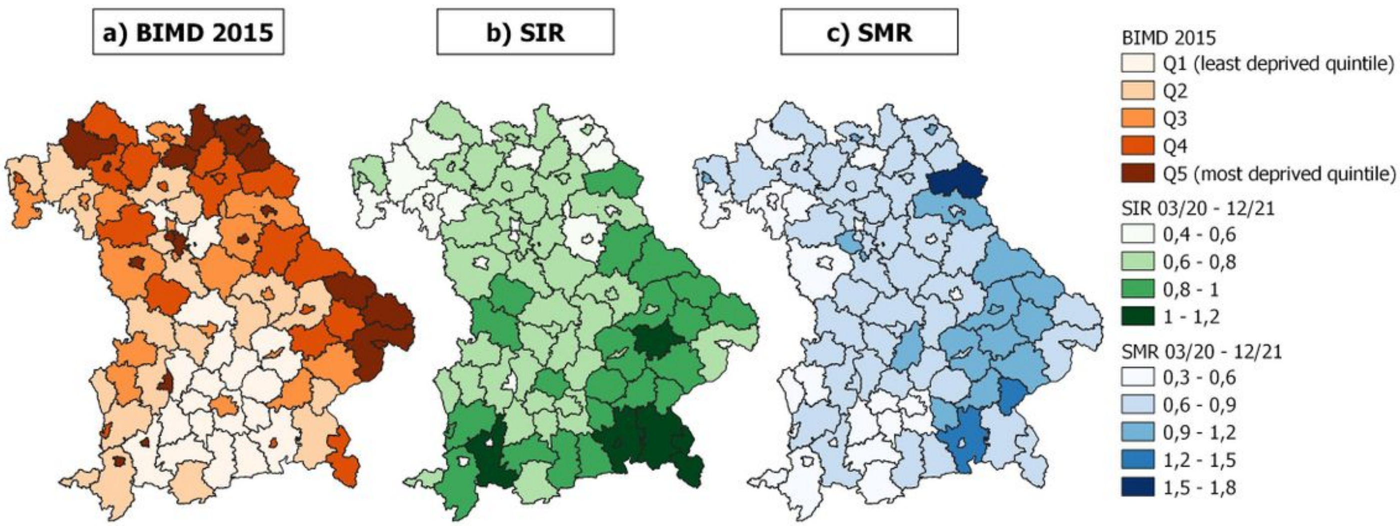

Figure 1

Maps of area deprivation and standardised incidence and mortality ratios in Bavaria, Germany

a) Bavarian Index of Multiple Deprivation for the reference year 2015 (BIMD 2015), b) standardised incidence ratio (SIR) and c) standardised mortality ratio (SMR) for the 96 districts in Bavaria, Germany. SIR and SMR were calculated for the period between 01/03/2020 and 31/12/2021.

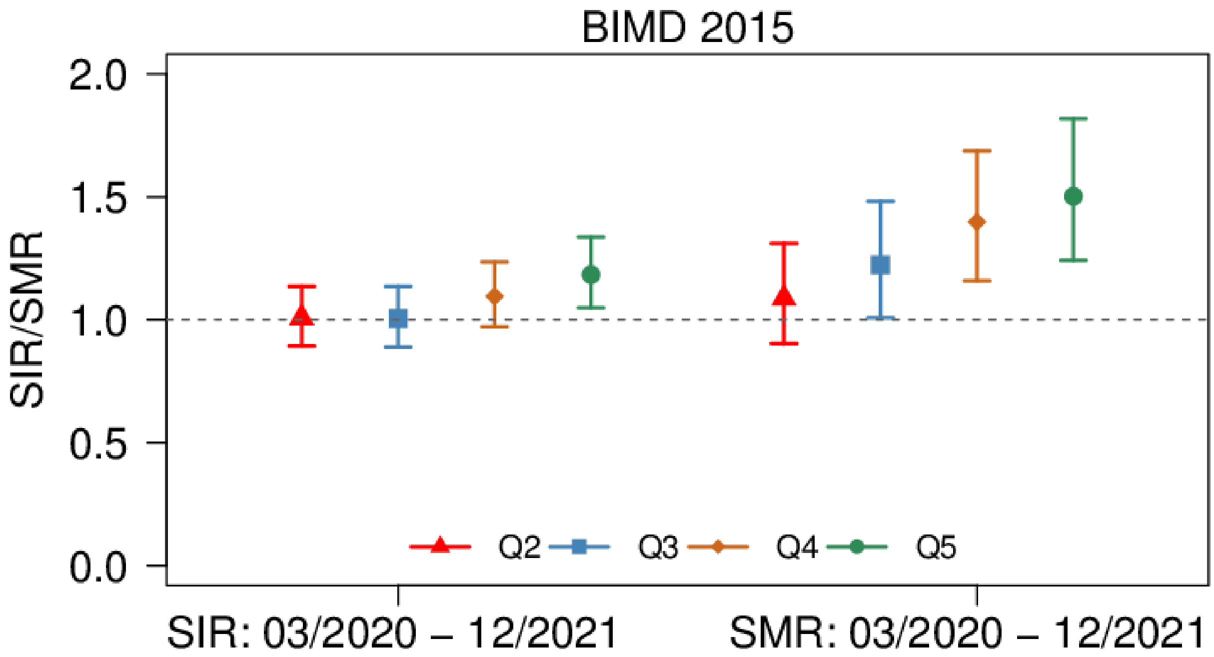

Figure 2

Strength of associations between area deprivation and standardised incidence and mortality ratios in Bavaria, Germany

Strength of associations between Bavarian Index of Multiple Deprivation (BIMD) 2015 and standardised incidence ratio (SIR) and standardised mortality ratio (SMR) for the 96 districts in Bavaria, Germany. Estimates for the period between 01/03/2020 and 31/12/2021 are shown for BIMD 2015 quintiles Q2 to Q5 (with Q1 = least deprived as the reference category) together with 95% confidence intervals. The estimates are adjusted for district and time.

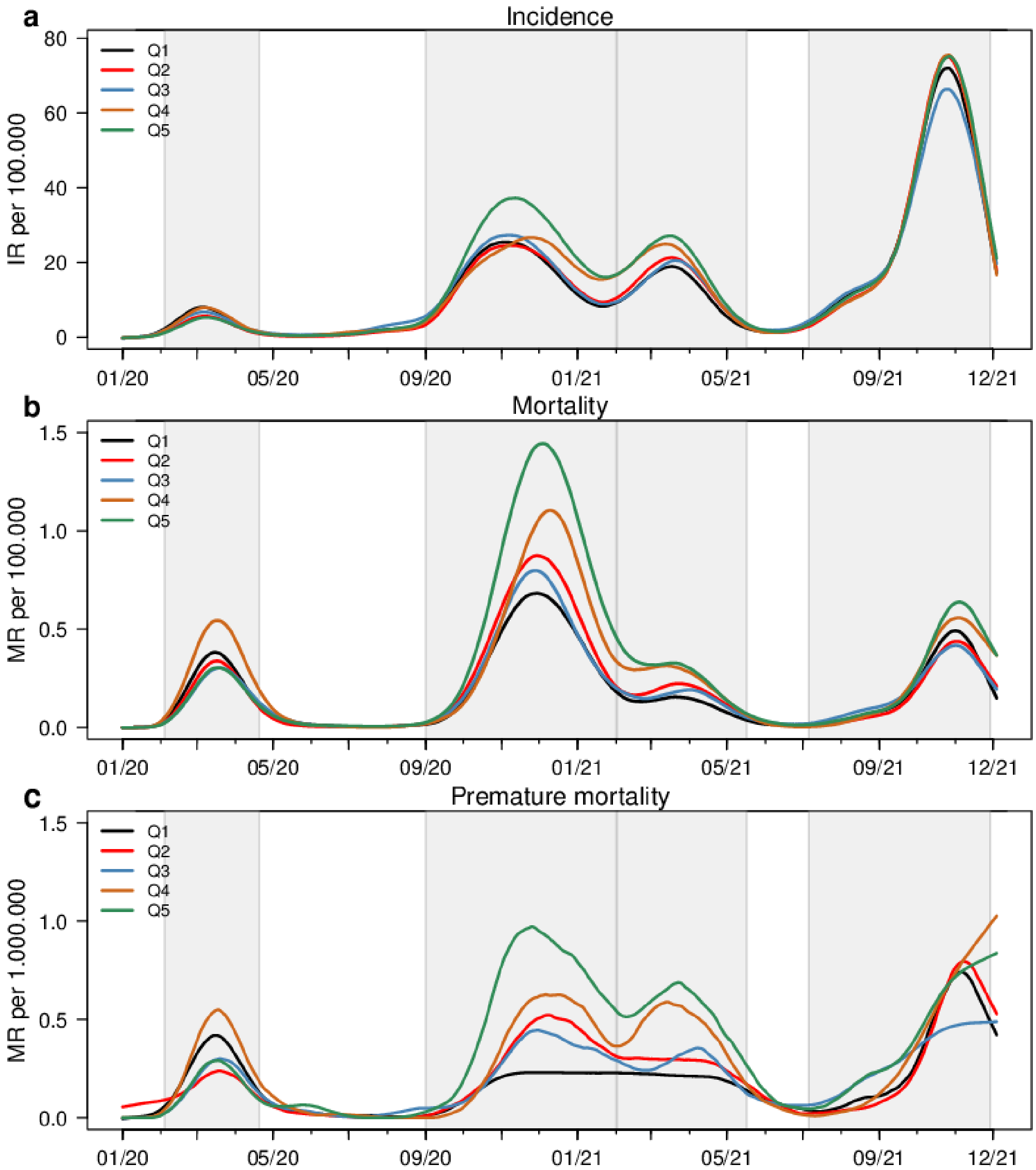

Figure 3

Incidence and mortality rates for BIMD 2015 quintiles in Bavaria, Germany

Daily reported incidence (a) and overall mortality rates (b) per 100,000 and premature mortality rates (in SARS-CoV-2 patients aged <65 years) in (c) per 1,000,000 population for districts belonging to each quintile of the Bavarian Index of Multiple Deprivation 2015 (BIMD 2015) between 2015 between January 2020 and December 2021 in Bavaria, Germany. Q1 describes the 20% least deprived and Q5 the 20% most deprived of all 96 districts. The time periods of the four infection waves are shown as light grey areas in the figure. IR = incidence rate, MR = mortality rate.

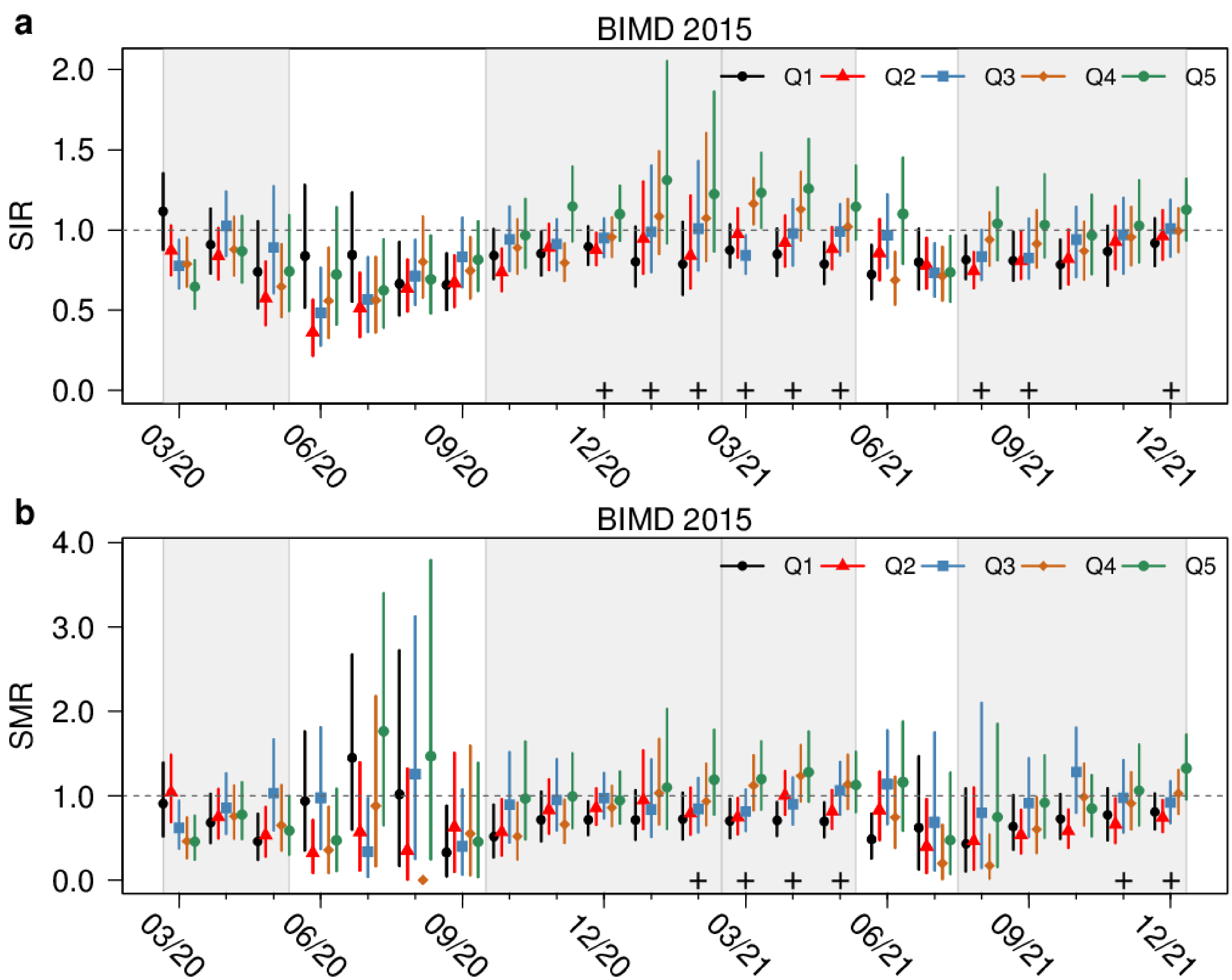

Figure 4

Standardised incidence and mortality ratios for BIMD 2015 quintiles in Bavaria, Germany

Standardised incidence ratios (SIR, a) and mortality ratios (SMR, b) of SARS-CoV-2 infections and related fatalities for quintiles Q1 (the 20% least deprived districts) to Q5 (the 20% most deprived districts) of Bavarian Index of Multiple Deprivation 2015 (BIMD 2015) between March 2020 and December 2021 in Bavaria, Germany. A plus sign (+) indicates a statistically significant increasing linear trend with increasing deprivation quantile. The time periods of the four infection waves are shown as light grey areas in the figure.

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