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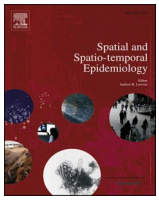

Original Research

The complex link between socioeconomic deprivation and COVID-19. Evidence from small areas of Catalonia

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ABSTRACT

This ecological study assesses the association between the incidence rate of COVID-19 confirmed cases and socioeconomic deprivation in the Catalan small areas for the first six waves of the pandemic. The association is estimated using Poisson regressions and, in contrast to previous studies, considering that the relationship is not linear but rather depends on the degree of deprivation. The results show that the association between deprivation and incidence varied between waves, not only in intensity but also in its sign. Although it was insignificant in the first, third and fourth waves, the association was positive and significant in the second, becoming significantly negative in the fifth and sixth waves. Interestingly, the evidence suggests that the link between both magnitudes was not homogeneous throughout the distribution of deprivation, the pattern also varying between waves. The results are discussed in view of the role of non-pharmacological interventions and vaccination, as well as potential biases (for example that associated with differences between population groups in the propensity to be tested in each wave).

1. Background

The differences between disadvantaged and wealthy places in the degree of incidence of COVID-19 aroused public and academic interest since the beginning of the pandemic. The media reported how residents of modest working-class districts in cities around the world were much more likely to get the disease than residents of affluent districts, separated by only a few miles (Davies, 2020). In parallel, from very early stages of the pandemic, several academic studies emphasized the role of income and, more generally, of social and economic deprivation in the intensity with which COVID-19 impacted local populations. For example, in the case of the city of Barcelona, Baena-Diez et al. (2020) confirmed that between February 26, 2020 and April 19, 2020, the districts with the lowest average income had the highest incidence rate of confirmed cases, while those of higher income had the lowest incidence rates, concluding the need for the health system to pay special attention to the most deprived areas. In the same vein, using information from New York neighbourhoods during the first weeks of the pandemic, Borjas (2020) showed that the probability (conditional on being tested) of testing positive was much higher for people who lived in poor neighbourhoods. Similar results have been provided for cities and small areas around the world (e.g., Morrissey et al., 2021 for the UK; Maroko et al., 2020 for New York and Chicago; Madhav et al., 2020 for Louisiana; Mena et al., 2021 for Santiago, Chile; Molina-Torres et al., 2021 for Mexico City; Gullón et al., 2022 for Madrid). The socioeconomic gradient in the incidence of the pandemic can be explained by differences between places in material circumstances and related conditions of daily life, which increased the risk of COVID-19 infection, and by uneven general health and nutritional status, which affected the risk of severe disease and death (Burström and Tao, 2020).

Many of these studies have not paid enough attention to the complex role of differences between places in the level of income and, more generally, in the degree of socioeconomic deprivation. Specifically, they have overlooked that the association between deprivation and incidence rates may be non-linear and that the non-linear pattern may well have changed over the different waves of the pandemic. Besides, when estimating the association between deprivation and incidence, many previous ecological studies have not considered the simultaneous influence of other contextual determinants of the incidence of COVID-19 or have accounted for a rather limited set of these factors. Although some of these studies have used very comprehensive measures of deprivation that include some controls of the context, the extant literature has emphasized the role of other elements of each place not usually incorporated in those measures. Among others, climatic and environmental conditions (Chen et al., 2021; Xu et al., 2021), population density (Smith et al. 2021; Martins-Filho, 2021), the demographic composition of the

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population (López-Gay et al., 2022; Jatrana et al., 2022), and even characteristics of the health system and the quality of regional institutions (Rodríguez-Pose and Burlina, 2021; Díaz Ramírez et al., 2022). Given that these factors are likely to be correlated with socioeconomic deprivation, empirical analyses that have not controlled for their relationship with the incidence rate would have been estimating the *gross* association between deprivation and the incidence rate. In other words, the existing evidence about the association conditional to the effect of these confounders derived from ecological studies is somewhat limited.[1]

Against this background, this study aims to provide further evidence on the relationship between geographical differences in socioeconomic deprivation and the spatially disparate incidence of COVID-19. It uses a socioeconomic deprivation index and administrative data on COVID-19 confirmed cases per 100,000 persons in the Basic Health Areas (BHAs) of Catalonia for the first six waves of the pandemic (from beginning of March 2020 to beginning of April 2022). The use of data for the Catalan BHAs minimizes heterogeneity in relation to some potential determinants of COVID-19 incidence (particularly regarding the characteristics of the health system and the social and institutional context), nevertheless preserving notable variability in the incidence of the pandemic and socioeconomic deprivation. Using area-level socioeconomic deprivation instead of average income, the analysis is aligned with those who have used deprivation as a determinant of the general health condition and the incidence of other diseases (Stafford and Marmot, 2003; Havard et al., 2008; Juhász et al., 2010; Lamnisos et al., 2019; Charlton et al., 2013; Foster et al., 2018; Naughton et al., 2021; Silva et al., 2023). Socioeconomic deprivation has been claimed to be more closely linked to health status than just poverty, and income alone is likely to be an inadequate measure of socioeconomic status (Dunlop et al., 2022). In fact, some previous studies have analysed the effect of area-level deprivation on the incidence of COVID-19, concluding that greater deprivation is associated to a higher incidence and severity of the disease in the population (Madhav et al., 2020; Mena et al., 2021; Gullón et al., 2022; Moissl et al., 2022; Rohleder et al., 2022).

Unlike most previous studies we are aware of, this one explores the non-linear relationship between socioeconomic deprivation and incidence of COVID-19. As Galster (2008) emphasizes, the effects of a local phenomenon are very likely to occur in a non-linear fashion. Therefore, the empirical analysis we conduct allows the intensity and even the sign of the association between deprivation and incidence to vary between areas depending on their degree of deprivation. To be clear, we consider that this association may be larger (or smaller) in areas of high deprivation than in areas of low deprivation. And even that the sign of the association can be different in both types of places. As discussed below, there are arguments as well as related evidence from previous pandemics that support this methodological decision. It is important to emphasize that, if this heterogeneity in the association throughout the distribution of area-level deprivation is confirmed, the estimates in the literature based on linear associations would have provided incomplete evidence of the relationship between deprivation and incidence of the disease.

The study analyses the association between area-level socioeconomic deprivation and the incidence rate of COVID-19 confirmed cases throughout six waves, which cover a period that extends from the initial outbreak of the pandemic in Catalonia to two years later, when more than 80 % of its population was fully vaccinated. Therefore, it goes beyond studies that have explored the relationship between deprivation and COVID-19 using data from only the first waves (even from the first weeks of the coronavirus outbreak). And while it is true that some recent studies have considered the change in the effect of some factors at various points in time (Arauzo-Carod, 2021; Bárcena-Martín, 2022; Bartolomeo et al., 2022; Ha and Lee, 2022) this study is more exhaustive when considering the possible changes in the two-year period that includes six waves, that are quite heterogeneous in various aspects, including non-pharmaceutical interventions (NPI), protection due to vaccination, and policies and access to testing. In this sense, the study closest to ours is that of Gullón et al. (2022), which analyses the relationship between deprivation and the incidence rate of COVID-19 confirmed cases in the BHAs of the city of Madrid until September 2021. Our results confirm the change in the association between both magnitudes over time and, in addition, show how the most important change in the relationship may have occurred in the last two waves, when a high percentage of the population was fully vaccinated, NPI were largely relaxed, and self-tests were available through private purchase. It is important to emphasize that, to our knowledge, this is the first ecological study of the relationship between deprivation and COVID-19 that controls for the proportion of the population vaccinated in the area.

Finally, the results of the study confirm the importance of controlling for other potential determinants of the prevalence of COVID-19. In fact, the evidence from the Catalan BHAs suggests that there was no significant association between deprivation and incidence for some of the waves after controlling for various confounders. This contrasts with previous studies that did not include controls, or that included them in a limited number (Baena-Díez et al. 2020; Gullón et al. 2022). As argued above, the deprivation index incorporates various factors related to the BHA population that may be correlated with other area-level characteristics and traits that, as shown by the previous literature (Madlock--Brown et al., 2022), could determine the COVID-19 incidence rate. Not considering these factors as controls in the statistical model may well confound the estimation of the relationship between incidence and deprivation, by incorporating the effect of these omitted factors (the so-called omitted variables bias –Wooldridge 2020). For this reason, we believe that this study reports estimates that are closer to the *true* association between the incidence rate of COVID-19 confirmed cases and the degree of socioeconomic deprivation.

2. Methods

2.1. Framework and data

Catalan BHAs are the spatial units under analysis. The BHA is the elementary territorial unit through which primary health care services are organized, based on geographic, demographic, social and epidemiological factors, particularly based on the population's accessibility to services and the efficiency in the organization of health resources. Information for the set of variables involved in the analysis was available for 357 out of the 374 BHAs[2], that cover most of the Catalan territory and its population. The average population (covered by the public health system) in a BHA is 20.6 thousand people, with a minimum of 2.4 thousand and a maximum of 63 thousand people. The use of Catalan BHAs minimises the risk of bias due to differences between places in the testing and counting of COVID-19 cases. The criteria and procedures for testing and considering positive cases were defined and implemented by the Spanish and Catalan health authorities in a homogeneous manner for the entire territory of Catalonia. Even so, there could be differences in testing between population groups that could induce bias in the estimation of the effect of deprivation as BHAs differ in the composition of

[1] This contrasts with studies that have analyzed the role of various drivers of exposure to SARS-CoV-2 using individual-level information (e.g., Larsen et al., 2023), as they usually include an extensive list of individual controls. However, the number of area-level factors included in the analysis is also rather limited in those studies.

[2] This was the total number of BHAs at the beginning of the COVID-19 pandemic. The BHAs excluded from the analysis (less than five percent) do not have specific characteristics or traits, so their exclusion should not bias the results due to sample selection.

their populations and deprivation varies between population groups. In any case, differences between population groups are smaller in the case of the Catalan territory than when considering more diverse territories, with heterogeneous NPI and variation in the share of population vaccinated, and the empirical model incorporates various controls for these potential differences between the BHAs.

The study covers the first six waves of the pandemic in Catalonia (see details in the Online Supplementary Material). In the absence of a *universal* definition of a wave of the COVID-19 pandemic (Zhang et al., 2021), an ad hoc criterion considering the evolution of the pandemic in the Catalan territory has been used. The set of NPI varied throughout the waves, but it did so in a homogeneous manner for all BHAs. The way infections were detected also varied between waves, although homogeneously for all Catalan BHAs. In the first four waves, tests were carried out, free of charge, in hospitals and other health facilities when individuals showed symptoms compatible with the disease and/or because direct contact with an infected person was reported. In the last two waves of the period analysed, additionally it was possible to use rapid self-tests, paid for by users. The positive results reported through self-tests in those waves were cases also activated by the epidemiological surveillance services of Catalonia. Likewise, it should be noted that COVID-19 vaccination began at the beginning of the third wave, so its effect affected the last four waves in the analysis. The statistical model includes a control for the differences between BHAs in the percentage of the population vaccinated in each wave.

The number of COVID-19 positive tests in each BHA for each wave was calculated from the number of daily cases of the "Record of COVID-19 tests performed in Catalonia. Segregation by gender and health area" Open Data of Catalonia, Health Department, Catalan Government. Population figures are from the "Catalan Health Service Central Population Register". This source reports the number of people insured in the (universal) public health system with residence in the corresponding BHA. The socioeconomic deprivation composite index was calculated by the Health Quality and Assessment Agency of Catalonia (Colls et al., 2020), while data on demographic and health status controls were compiled by the Catalan Government Health Department (Oliver-Parra and González-Viana, 2020). Weather and pollution data are from the "Statistical Yearbook of Catalonia". Finally, the number of doses of the COVID-19 vaccine are from the database "COVID-19 vaccination: administered doses by health area"—Open Data of Catalonia.

2.2. Outcome, independent variable, and controls

The incidence of positive tests for COVID-19 in each BHA is measured by the 14-day incidence rate (IR14) calculated as the number of reported COVID-19 confirmed cases per 100,000 inhabitants during the 14-day period prior to the peak of each wave.[3] In the robustness analyses, alternative measures were used, such as the incidence rate for the 7 days prior to the peak of the wave and the rate calculated using the total number of cases in each wave. Similar conclusions were obtained in all cases.

Socioeconomic deprivation of each BHA is measured by a composite index created for the allocation of the budgets of the primary healthcare teams in Catalonia, valid for both urban and rural environments. The index combines information from three variables related to income (population exempt from drug co-payment, population with income of less than €18,000, and population with income of more than €100,000), two variables related to occupation and education (population employed in low-skill jobs, and population with insufficient educational attainment), and two variables of the health status of the population (rate of premature deaths –before the age of 75–, and rate of potentially avoidable hospitalizations). High values of the index correspond to a greater degree of socioeconomic deprivation of the BHA population. Although it is not a multiple deprivation index, such as that of the English Indices of Deprivation 2019 (McLennan et al., 2019) or the European Index of Deprivation (e.g., Merville et al., 2022), it does incorporate indicators referring to various dimensions and has been used in several ecological studies on the role of socioeconomic factors in the incidence of different diseases in Catalonia (Agustí et al., 2020; Serra-Pujades et al., 2021).

To isolate the partial association between area-level socioeconomic deprivation and incidence of the coronavirus, the study includes an extensive list of controls. First, the statistical model accounts for differences between areas in weather conditions (temperature and relative humidity) and air pollution (PM10 and NO2), as several studies have suggested that they may have affected the spatial spread of the SARS-CoV-2 and caused differences between locations in the severity of its impact (Ganslmeier et al., 2021; Xu et al., 2021). Second, the model includes population density. In the absence of interventions that significantly reduce people's mobility, particularly in the first waves, higher population density has been shown to correlate with greater transmission of SARS-CoV-2 in the area (Smith et al., 2021). Third, the percentage of the population over 65 years of age, an index of over-aging of the area population, and the percentage of older people living alone are included as demographic controls. Differences in population age structures have been pointed out as a fundamental factor in explaining the spatial disparities in the incidence and mortality of COVID-19 (Kashnitsky and Aburto, 2020). To be clear, the impact of the disease has been particularly high in places of aging populations (Rodríguez-Pose and Burlina, 2021). In addition, the empirical model includes two indicators of the health status of the BHA population—the percentage of the population over 15 years of age with a disability and the percentage of the population with a negative self-perception of health–, and life expectancy, distinguishing by gender. Although the composite index of socioeconomic deprivation does include indicators of health status, we believe it is important to include these health-related controls given that several underlying medical conditions have been identified as the cause of severe COVID-19 illness in adults (Kompaniyets et al., 2021). To be clear, certain types of morbidity, more common among people in deprived areas, are likely to positively correlate with COVID-19 incidence rates. Controlling for them is especially important in the early stages of the pandemic when only severe cases requiring medical treatment were tested in Catalonia. The statistical model also controls for the number of doses of the COVID-19 vaccine administered to the population of each BHA. This accounts for differences in vaccination rates across places that, since the third wave, could have affected the incidence of COVID-19. The vaccination rate can also capture differences in various personal and contextual factors that can correlate with the incidence rate and the degree of BHA deprivation. Finally, it should be emphasized that control for potential confounders is particularly important in the case of using a deprivation index that is based on a limited number of characteristics of the BHA population.

2.3. Statistical model

Poisson regressions are used to estimate the relationship between area-level socioeconomic deprivation and COVID-19 incidence rate:

$$\mu_{a,w} = exp\left[\beta_{0,w} + \beta_{1,w}\cdot SocEcoDepr_a + \beta_{2,w}\cdot SocEcoDepr_a^2 + Controls_a\cdot\delta_w + ln(Pop)_a\right]$$

where $\mu_{a,w} = E(Cases\_Covid19_{a,w}|X_a)$, *SocEcoDepr* is the index of socioeconomic deprivation, *Controls* is the vector of control variables, and *Pop* refers to population, the exposure variable. Subscripts *a* and *w* refer to BHA and wave respectively. The square of the deprivation composite indicator is included to account for the potential non-linearity of its effect on the incidence of COVID-19. It should be noted that, in this

[3] Following the recommendation of Guo (2011), the regression analysis uses crude incidence rates and includes controls for the demographic structure of each BHA instead of using age-standardized incidence rates.

flexible specification, the coefficients of the deprivation regressors, $\beta_{1,w}$ and $\beta_{2,w}$, and the controls (δ_w) are allowed to vary between waves. Alternative, less flexible specifications (equal coefficients of deprivation and/or controls across all six waves), have also been considered. However, as shown in the Online Supplementary Material, statistical tests confirm the superiority of the specification that allows the variability of all coefficients. This material also shows how the model that includes the square of the deprivation index is clearly preferred to one that only includes the index in a linear manner. The average partial effect (APE) and the partial effect in various percentiles of the deprivation distribution (PE) are obtained from the estimation of the corresponding coefficients for each wave, jointly with the corresponding robust standard errors and p-values (see details in the Online Supplementary Material). Since high values of *SocEcoDepr* correspond to a higher level of deprivation, a positive (negative) partial effect indicates that greater deprivation was associated with a higher (lower) incidence rate. The statistical analysis was carried out using the commands `Poisson` and `margins` in Stata v17.0.

3. Results

The COVID-19 pandemic has had a geographically uneven incidence in Catalonia. Additionally, the geographic distribution of the IR14 evolved along the different waves. This is clearly seen in the boxplots (Fig. 1) and in the choropleth maps (Fig. 2) of the incidence rates in the BHAs in the first and last waves under analysis (information for all waves available in the Online Supplementary Material). Similarly, Fig. 3 confirms the marked geographical differences in the degree of deprivation.

The results of the estimation of the partial effects of socioeconomic deprivation for each wave from the Poisson regressions that include the set of contextual controls are reported in Table 1.[4] The first row reports the APEs. It is positive but small and not statistically significant in the first wave, whereas a positive and statistically significant APE, of large size, is estimated for the second wave. Regarding the following waves, on average, there does not seem to be a relevant relationship between deprivation and incidence in the third and fourth. In sharp contrast, the association between both magnitudes became intense and significant again in the last two waves. What is even more important in this case is that the relationship turned negative. In addition, the effect is sizeable, especially in the case of the fifth wave.

The second block of rows in Table 1 reports the PEs in different points of the deprivation distribution. In general, there is remarkable variability in the size and significance of PEs across waves. The intensity of the relationship decreased with the level of deprivation in the first wave. Indeed, the PE is only (marginally) significant at the 10th percentile. On the contrary, the relationship between deprivation and incidence increased across the distribution in the second wave. While the PE is small and not significant in the BHAs with the lowest levels of deprivation, the effect is sizeable and clearly significant in those with the highest deprivation. An interesting variation of the PE along the deprivation distribution is also observed in the third wave. In this case, the association in the upper part of the distribution has a different sign than that in the middle and lower parts. While an increase in deprivation would have been associated with a decrease in COVID-19 incidence of confirmed cases in areas with low deprivation, the relationship would have been of the opposite sign in highly deprived areas. A similar, though less intense, pattern is observed in the case of the fourth wave. Finally, the PEs in the fifth and sixth waves confirm the variability of the effect along the deprivation distribution and the differences between waves. The estimated effect is negative in all cases, but while its intensity decreased with the degree of deprivation in the fifth wave, the results suggest that the opposite happened in the sixth.

[4] Results of the estimation of the full set of regression coefficients are reported in the Online Supplementary Material. It also reports and discusses the results of estimating alternative (less flexible) specifications.

4. Discussion

This section first acknowledges some limitations of the study and then discusses the results.

First of all, it can be argued that the omission of some area-level factors may have distorted the estimate of the association between deprivation and COVID-19 incidence. However, the homogeneity of the BHAs in many aspects and the extensive list of controls considered suggest that this distortion should not be very large. Besides, the study uses official administrative data on positive cases and is therefore affected by changes on testing policies and access to tests throughout the waves. Although the impact of these changes is minimized when estimating the association between deprivation and incidence with the data from each wave separately, it may be affected by differences in the propensity to get tested between population groups in each wave. Unfortunately, lack of data has prevented considering non-randomness in testing and thus estimating the effect of deprivation on the conditional probability of a positive test result. Data on excess mortality from BHAs was also not available, so we could not use it as an indicator of the local impact of COVID-19. It would be interesting to check if the heterogeneity of the effect along the distribution of deprivation also occurred in mortality caused by COVID-19.

Regarding the deprivation indicator used in the study, it must be recognized that it is not an index of multiple deprivation, so it does not incorporate some domains that can be considered important to approximate the degree of socioeconomic deprivation from an ecological perspective. Although it considers some of the dimensions that may reasonably have determined the geographically differentiated impact of the COVID-19 pandemic (such as income, employment status, educational level, and potential vulnerability linked to the health status of the population), future studies should verify the validity of the results when using indices that consider additional domains. In a similar vein, it would be interesting to check the robustness of the results when the association between deprivation and incidence of COVID-19 is estimated using smaller spatial units than those used in this study. Data on COVID-19 positive tests is only available for Catalan municipalities and BHAs, which has prevented us from carrying out the analysis for smaller spatial units. However, in the case of the urban area of Barcelona, the BHAs roughly correspond to neighbourhoods. When replicating the exercise with that subset of BHAs, the results are in line with those obtained for all BHAs, which suggests that the conclusions apply in the case of smaller (local) areas.

Poisson regressions can lead to inadequate estimates in the case of overdispersion. To account for this, we estimated the partial effects using negative binomial regressions as a robustness check. Similar results were obtained for all waves. Finally, it should be noted that the study has not considered spatial dependence in the Poisson regressions. To deal with its potential effect on the estimation, the standard errors clustered by the upper geographical area (the 28 health sections of Catalonia) were computed. Using them, instead of simple robust standard errors, to assess the significance of the partial effects did not lead to any substantial change.

The results of this study confirm the association between area-level deprivation and the incidence rate after controlling for the influence of other contextual determinants of the prevalence of the pandemic, although not in all waves. In fact, the results are only partially consistent with the view that socioeconomic deprivation and incidence of COVID-19 are positively related. This would be the case only in the first waves, when uncertainty about the disease and the mechanisms of its spread was greater and the resources and means to fight it effectively were scarcer. In these circumstances, places with populations with lower income and educational attainment, employed in jobs with high social interaction and few teleworking options, together with a worse health

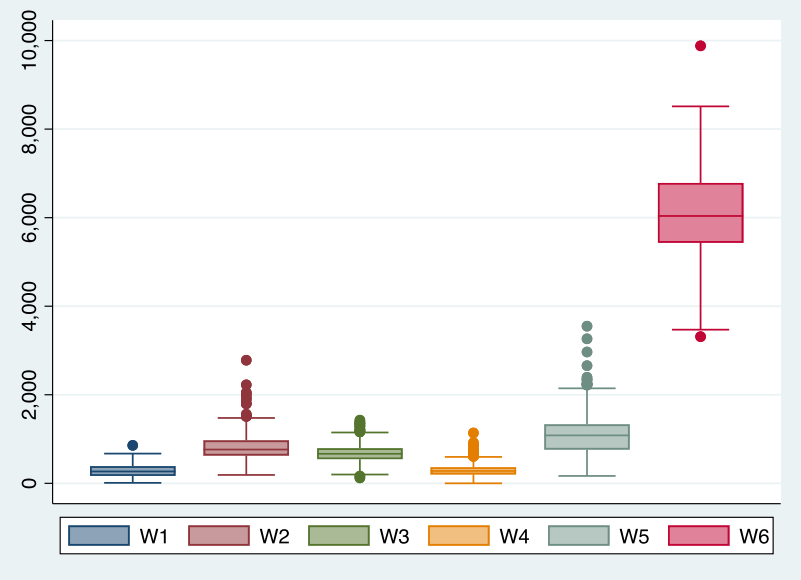

Fig. 1. Distribution of the local IR14 in the six waves.

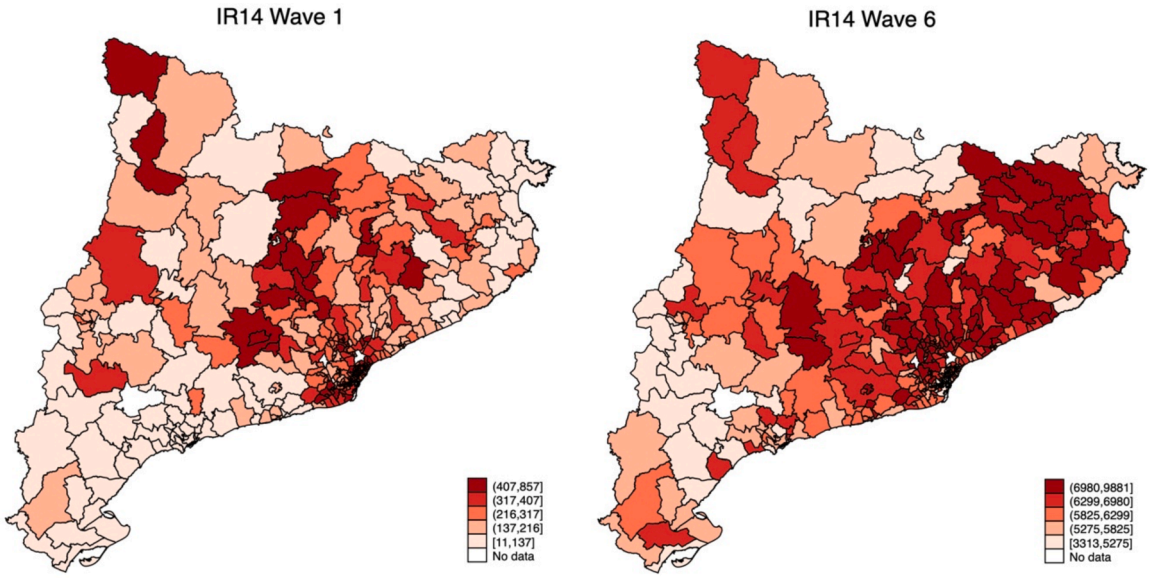

Fig. 2. Choropleth maps of IR14 in the first and last waves (the darker/lighter the colour, the higher/lower the IR14).

status and low awareness of the importance of health care, were more decisive than in later waves in which both information and resources improved substantially. In sharp contrast to the initial waves, the relationship would have turned negative for the last two waves—confirming the indications of Gullón et al. (2022) for June and July 2021 in the case of the city of Madrid. A possible explanation for this negative relationship has to do with mass vaccination and the relaxation of community NPIs in the last two waves. Widespread vaccination would have contributed to reducing the risk of suffering serious health complications in the event of contagion throughout the Catalan territory, regardless of the level of deprivation in each area. In fact, it has been shown that mass vaccination reduced socioeconomic COVID-19-related inequalities in Catalonia (Roel et al., 2022). At the same time, the relaxation of community NPIs allowed the resumption of indoor social activities (e.g., nightclubs, restaurants, museums, gyms, theatres, concert venues) and vacation trips that produced an increase in mobility and close contacts. To the extent that these activities have been more frequent among the population in less deprived areas (Mak et al., 2021; Cunillera Puértolas et al., 2022), they would have facilitated the spread of the virus with greater intensity than in areas of high deprivation. Furthermore, it is important to keep in mind that in the last two waves self-tests were accessible through private purchase and that to travel and participate in many social activities, it was necessary to prove the absence of contagion. Thus, at least part of the differences in the incidence rate observed in the last two waves could be due to differences between more and less deprived areas in self-testing uptake (Green et al., 2021).

The lack of a significant association for the first wave is striking and deserves a comment. In fact, the evidence from this study do not match that of previous studies that focused on the first weeks of the outbreak in Barcelona, the main city of Catalonia. Baena-Díez et al. (2020) reported a positive and significant association between incidence of confirmed cases and income. The results in this study for the same period obtained using the observations of the BHAs of the city of Barcelona confirm the

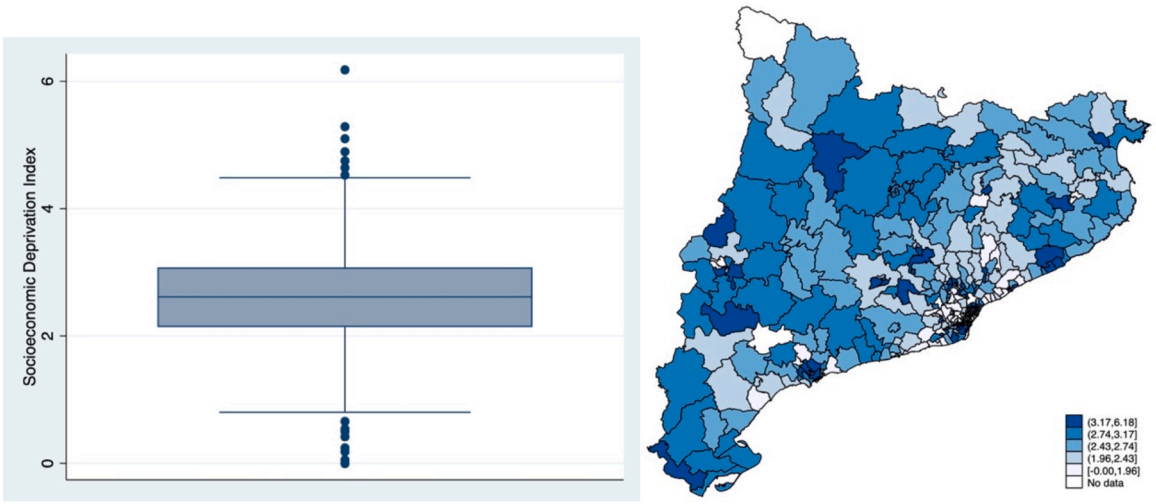

Fig. 3. Distribution of the local socioeconomic deprivation index (the darker/lighter the colour, the higher/lower the deprivation index).

Table 1
Partial effects of the socioeconomic deprivation index.

	Wave 1	Wave 2	Wave 3	Wave 4	Wave 5	Wave 6
APE	8.331	95.225***	−8.968	11.185	−242.950***	−163.349***
PE at percentiles of socioeconomic deprivation index						
p10	18.792*	30.378	−72.192***	−2.240	−341.666***	−83.748
p25	12.430	65.565***	−30.677**	6.002	−268.016***	−136.447**
p50	8.147	90.294***	−7.554	11.193	−231.751***	−167.493***
p75	3.764	118.153***	14.797	16.625*	−201.401***	−196.783***
p90	−2.666	167.099***	48.508***	25.044*	−165.200***	−236.462***
Avrg IR14	277.30	833.26	680.34	301.80	1095.36	6078.92

Note: All regressions include the full set of controls described in the text. Figures denote estimated partial effects on the IR14 (per 100 K inhabitants). Avrg IR14 refers to the average of the IR14 in the set of Catalan BHAs.
*** $p < 0.01$,
** $p < 0.05$,
* $p < 0.1$.

lack of significance of the association with deprivation. This shows the importance of considering the multidimensional character of deprivation and the need for ecological studies to control for confounding contextual factors. Similar arguments may explain the difference with results for the first wave in Arauzo-Carod et al. (2021). In this case, we have obtained comparable results when excluding from the list of controls those referring to weather, pollution, and health status. This suggests that the exclusion of these controls would be confounding the estimation of the specific association between deprivation and COVID-19 incidence rate. That is, in the first wave, BHAs with similar population density, environmental and weather conditions, demographic structure, and health status would have had approximately the same incidence rate regardless of their degree of deprivation. In contrast, in the second wave, with much more knowledge of the threat, inequalities would have grown due to asymmetries between places in the effective implementation of public health measures to combat the disease such as sheltering at home, adhering to social distancing guidelines and reductions in close contacts (Clouston et al., 2021; Wei et al., 2023).

Additionally, the results strongly confirm that the association between deprivation and incidence rate has not been uniform throughout the distribution of area-level deprivation. Some arguments in previous studies support a non-linear relationship between socioeconomic deprivation and the prevalence of COVID-19 and similar diseases. For example, it is reasonable to think that, especially at some stages of the pandemic, the risk of contagion would have been low in places with the highest level of deprivation if low deprivation is associated with high unemployment, and this reduces work-related interactions. In this regard, Grantz et al. (2016) argued that unemployment had a protective effect on influenza mortality and was associated with decreased transmission during the 1918 flu pandemic in Chicago's census tracts. As Gullón et al. (2022) point out in the case of Madrid and Vitale (2022) reports in the case of Montreal, for areas with a somewhat lower level of deprivation, the incidence would have been higher since their inhabitants had jobs characterized by frequent and intense social interactions, little possibility of teleworking and use of public transport to travel to/from the workplace. Therefore, compared to the places with the greatest deprivation, those with a somewhat better socioeconomic situation could have suffered a higher incidence. On the contrary, the incidence would have been lower in the least deprived places given that their population has occupations with less need for interactions, susceptible to teleworking and with alternatives to collective transport. This pattern, based on individual-level characteristics, suggests an inverted U-type association between deprivation and incidence of COVID-19 at the area-level that, however, in the case of the Catalan BHAs is only seen, partially, in the first wave. In fact, our results show that the increase in the incidence rate associated with a rise in BHA deprivation intensified with the level of deprivation very clearly in the second wave. In the face of high community transmission, the increase in deprivation was associated with moderate growth in incidence in settings with low levels of deprivation. Instead, the reaction would have been more intense in places with intermediate deprivation and would have reached very high values in the upper part of the deprivation distribution.

The evidence for the following waves confirms the changes in the pattern of the association between the incidence rate and the

distribution of deprivation. The study has shown how the lack of association in the average in the third wave hides a negative relationship in the most deprived places that becomes positive and significant in the less deprived ones. Although not as clear, this pattern is also seen in the fourth wave. On the contrary, it changed radically in the last two waves. The association was negative regardless of the degree of area-level deprivation in the fifth and sixth waves. But while in the fifth the increase in the incidence rate associated with a rise in deprivation was greater in the less than in the most deprived places, in the sixth wave the opposite situation occurred, since the intensity of the association increased with the degree of deprivation. Taken together, the results confirm that the partial association between deprivation and incidence has varied between areas throughout the different waves, depending on the degree of deprivation. They suggest that, even though the NPIs were adopted and relaxed in a uniform and simultaneous manner throughout the Catalan territory, and that the vaccination schedule was also geographically homogeneous, both types of interventions would have had a place-specific effect that would have depended on the degree of area-level deprivation.

5. Conclusion

This study confirms that the effect of area-level deprivation on incidence of COVID-19 confirmed cases may have been more complex than suggested by previous research. The results point to important differences between waves in the association between them, which is not limited to the intensity of the relationship but also to its sign. To be clear, deprivation and incidence rate only had a significant relationship in the second, fifth and sixth waves. But while in the second wave the association was positive, it became negative in the fifth and sixth waves. Furthermore, the relationship between the incidence rate and deprivation was not uniform along the distribution of deprivation, with a pattern that also varied between waves. Although we cannot rule out that some of the discrepancies are due to differences between the BHAs in the propensity to be tested, evidence suggests that NPI and vaccination may have moderated the effect of socioeconomic deprivation on the incidence of COVID-19 in the Catalan BHAs.

CRediT authorship contribution statement

Enrique López-Bazo: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Software, Validation, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.sste.2024.100648.

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