Public Health 227 (2024) 9–15

Contents lists available at ScienceDirect

Public Health

journal homepage: www.elsevier.com/locate/puhe

Original Research

Spatiotemporal variability in socioeconomic inequalities in COVID-19 vaccination in Catalonia, Spain

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ARTICLE INFO

Article history:
Received 13 June 2023
Received in revised form
30 October 2023
Accepted 10 November 2023
Available online 14 December 2023

Keywords:
COVID-19
Vaccination
Socioeconomic inequalities
Joint spatiotemporal models
Unobserved confounding

ABSTRACT

Objectives: Socioeconomic inequalities have played a significant role in the unequal coverage of the COVID-19 vaccine. The objectives of this study were to (1) assess the socioeconomic inequalities in COVID-19 vaccination coverage in Catalonia, Spain; (2) analyse the spatial variation over time of these inequalities; and (3) assess variations in time and space in the effect of vaccination on inequalities in COVID-19 outcomes.
Study design: A mixed longitudinal ecological study design was used.
Methods: Catalonia is divided in to 373 Basic Health Areas. Weekly data from these Basic Health Areas were obtained from the last week of December 2020 until the first week of March of 2022. A joint spatio-temporal model was used with the dependent variables of vaccination and COVID-19 outcomes, which were estimated using a Bayesian approach. The study controlled for observed confounders, unobserved heterogeneity, and spatial and temporal dependencies. The study allowed the effect of the explanatory variables on the dependent variables to vary in space and in time.
Results: Areas with lower socioeconomic level were those with the lowest vaccination rates and the highest risk of COVID-19 outcomes.
In general, individuals in areas that were located in the upper two quartiles of average net income per person and in the lower two quartiles of unemployment rate (i.e., the least economically disadvantaged) had a higher propensity to be vaccinated than those in the most economically disadvantaged areas. In the same sense, the greater the percentage of the population aged ≥65 years, the higher the propensity to be vaccinated, while areas located in the two upper quartiles of population density and areas with a high percentage of poor housing had a lower propensity to be vaccinated.
Higher vaccination rates reduced the risk of COVID-19 outcomes, while COVID-19 outcomes did not influence the propensity to be vaccinated. The effects of the explanatory variables were not the same in all areas or between the different waves of the pandemic, and clusters of excess risk of low vaccination in the most disadvantaged areas were detected.
Conclusions: COVID-19 vaccination inequalities in the most disadvantaged areas could be a result of structural barriers, such as the lack of access to information about the vaccination process, and/or logistical challenges, such as the lack of transportation, limited Internet access or difficulty in scheduling appointments. Public health strategies should be developed to mitigate these barriers and reduce vaccination inequalities.

Introduction

Despite the efforts of all countries to guarantee a fair and equitable COVID-19 vaccination process, there is some evidence that socioeconomic inequalities have played a significant role in the unequal coverage of the vaccine. In fact, people living in the most socioeconomically disadvantaged areas had the highest incidence of COVID-19[1,2] and also the lowest vaccination rate.[3]

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https://doi.org/10.1016/j.puhe.2023.11.024
0033-3506/

There are many reasons why socioeconomic inequalities could result in unequal coverage of the vaccine. First, barriers may exist in terms of access to the vaccine for low socioeconomic status and minority populations.[4,5] Among these, it is worth mentioning the location of vaccination sites, since, spatial proximity to services can affect their use. People with a low socioeconomic level may have barriers in accessing the Internet, through which most vaccination appointments were made.[4,5] People with a more precarious job and/or without paid sick leave may have difficulties taking time off to get the vaccine, especially given long or uncertain wait times that could force missed hours of work, perhaps resulting in a loss of income. Those without a regular job may even fear losing their job.[4,5] Inequalities could also be impacted by the eligibility schedule, which initially focused on healthcare workers and older adults.[5] Finally, vaccine hesitancy, which has been reported to be greater in the population with low socioeconomic status, could also result in vaccination disparities.[6]

Spain has been one of the leaders in the European Union in terms of percentage of population vaccinated. In Catalonia, Spain, on 29 March 2023, 84.39 % of the population had received at least one dose of the COVID-19 vaccine and 82.67 % had received the complete regimen (i.e. full dose). Despite these figures, 6 months after the start of vaccine rollout, vaccination coverage differed by socioeconomic deprivation index quintiles.[3]

However, did these inequalities persist at later stages of vaccination (i.e., for full and booster doses)? If they were not maintained, did they vary similarly across the territory or did they vary spatially? A very small number of studies analyse the dynamics of vaccination inequalities over time[7,8] or in space,[9,10] but none explore the question of whether the variation of vaccination inequalities over time might not be homogeneous for the entire study territory.

This study aimed to answer these questions. The study hypotheses were that: (1) the inequalities in vaccination coverage varied throughout the territory (i.e., spatially and over time); (2) these variations were not independent (i.e., the variation over time of the coverage was not the same throughout the territory); and (3) the effect of vaccination on COVID-19 outcomes also varied over time and space. Therefore, the main objectives of the study were to assess the existence of socioeconomic inequalities in COVID-19 vaccination coverage in Catalonia, Spain, as well as to analyse the spatial variation over time of these socioeconomic inequalities. In addition, the study assessed variations in time and space on the effect of vaccination on inequalities in COVID-19 outcomes.

Methods

Study design

A mixed longitudinal ecological study design was used. Catalonia is divided in to 373 Basic Health Areas (ABS, is the acronym in Catalan and will be used from here on). Weekly data from these ABSs were obtained from the last week of December 2020 until the first week of March of 2022. The ABSs are the elementary territorial unit through which primary health care services are organised.[11,12]

Variables

Outcome variables

Two sets of outcome variables were considered: vaccination variables and COVID-19 outcome variables.

Vaccination variables included the weekly cumulative vaccination rate of one dose of COVID-19 vaccine (for those vaccines that required more than one dose), full dose (one or two doses, depending on the type of vaccine) and of booster doses. This study did not distinguish between the different COVID-19 vaccines available in Spain. The denominator for calculating the cumulative rate was the target population for each ABS. That is, the population that, according to the vaccination schedule, were allowed to be vaccinated that week (see Supplementary material).

The COVID-19 outcome variables were the number of new cases diagnosed that week (incidence), hospitalised cases, those admitted to the intensive care unit (ICU) and deaths. COVID-19 hospitalisations were defined as hospitalisations with a positive SARS-CoV-2 test between 21 days before and 3 days after the date of admission. COVID-19-related deaths were defined as deaths occurring no later than 28 days after the date of infection.

All data were obtained from the open data portal of the Government of Catalonia.[13]

Explanatory variables

The main explanatory variables of inequalities in vaccination were considered to be socioeconomic variables. In this study, the following contextual variables were included (further details can be found elsewhere[12]):

(i) Average net income per person (in Euros). Average of the years 2015–2019. Variable observed at the census track level (Source: INE[14]).
(ii) Gini index (in percentages) [a measure of the distribution of income across a population]. Average of the years 2015–2019. Variable observed at the census track level (Source: INE[14]).
(iii) Unemployment rate in 2011 (in percentages). Variable observed at the census track level (Source: INE[15]).
(iv) Percentage of the population aged $\geq$65 years. Average of the years 2015–2019. Variable observed at the census track level (Source: INE[14]).
(v) Poor housing. Percentage of houses with less than 45 m^2 of living area in 2011. Variable observed at the census track level (Source: INE[15]).
(vi) Percentage of foreigners from countries with medium and low human development index according to the United Nations Development Program.[16] Average of the years 2015–2019. Variable observed at the census track level (Source: INE[14]).
(vii) Population density in 2020 (in inhabitants/km^2). Variable observed at ABS level (Source: INE[17] and IDESCAT[18]).

Except for population density, all other variables were observed at the census tract level. Using the population of each of the census tracts as weights (the source of the total population of the census tract and of the population of the census tract by sex was INE[17]), the weighted average of the values at the census tracts that composed the ABS were calculated to obtain their value at ABS level.

This study also hypothesised that the weekly cumulative vaccination rate may be influenced by the COVID-19 outcome variables.

Data analyses

In both sets of outcome variables, the count data for several ABSs and for several weeks relied on small numbers of cases that, most likely, were over-dispersed. Therefore, this study assumed that the outcome variables were distributed following negative binomial distribution.

Maps of risk

To evaluate the existence of a geographical pattern in COVID-19 vaccination, this study represented the smoothed rates (sRates) on a map of the region under study (i.e., Catalonia). To estimate the sRates, a generalised linear mixed model (GLMM) was specified for the vaccination variables without including explanatory variables, but controlling for extra variability by including various random effects (and the target population as the offset). These random effects controlled for individual heterogeneity (i.e., unobserved confounders specific to the ABS and invariant in time), temporal dependency (i.e., the shape of the curve itself) and spatial dependency (i.e., the fact that small areas that are close in space show more similar values of the outcome variables than areas that are not close).

This study represented the sRates on the map of Catalonia by ABS in different waves. The map at the ABS level was obtained from the Department of Health, Government of Catalonia.[19]

Exceedance probabilities[20] were calculated which, in this case, were the probability that the smoothed rates were above the median of the accumulated percentage in each of the weeks. The exceedance probabilities were also represented on a map of the study area in different waves in order to assess the existence of agglomerations of excess (deficiency) cases (i.e., clusters).

Joint model for the outcome variables

Given that the COVID-19 outcomes were explanatory variables of the vaccination variables and these, in turn, were explanatory variables of the COVID-19 outcomes, sharing other explanatory variables, as well as random effects, a joint model must be specified. In particular, this study specified a joint GLMM model for each pair of outcomes variables; one from the set of vaccination variables (incidence, hospitalisation, ICU admissions and death) and one from the set of COVID-19 outcomes (one dose, complete schedule and booster dose). In both models, the contextual variables explained above were included.

Inference

Inferences were made following a Bayesian perspective, using the integrated nested Laplace approximation (INLA) approach.[21,22] Priors that penalise complexity (called PC priors) were used. These priors are robust in the sense that they do not have an impact on the results and, in addition, they have an epidemiological interpretation.[23]

All analyses were carried out using the free software R (version 4.2.2),[24] through the INLA package.[21,22,25] The maps were represented using the *tmap* package.[26]

Results

Descriptive statistics for the outcome variables are shown in Table S1 and Figure S1 in the supplementary material, and for the explanatory variables in Table 1. Table S2 in the supplementary material describes the evolution of the accumulated weekly percentage of the population vaccinated with one, full and booster doses.

In Fig. 1, maps of the smoothed rates of cumulative vaccination and the exceedance probabilities (probability that the smoothed rates were above the median of the accumulated percentage in each of the weeks) corresponding to the sixth wave (from the first week of November 2021) are shown. The maps corresponding to all of the waves are shown in the supplementary material (Figures S2 to S4).

Smoothed rates

The geographical divisions correspond to the Health Basic Areas (ABS).

In the one dose and full dose maps, the smoothed rates show a fairly similar pattern for the third and fourth quartiles located in the ABSs in western Catalonia and in the ABSs in the Barcelona metropolitan region in the east. Although the booster dose map also presents this pattern, there were more areas located in the third and, especially, the fourth quartiles. The exceedance probabilities maps show the existence of areas well below the median of the smoothed rates (less than 20 % probability, drawn in green) on the one dose map (30 % of all ABSs) and considerably less on the full dose map (3.9 % of all ABSs). Note that the same occurs with areas above the median (probability higher than 90 %), albeit to a lesser extent. In the booster dose map, there were no areas below or above the median.

If the socioeconomic characteristics of the ABSs are observed with a deficiency in accumulated vaccination cases (i.e., exceedance probabilities below 20 %), results show that for one dose they corresponded to more urban areas (Barcelona metropolitan area, on the central coast of the map; with the Vallès regions, to the west of the metropolitan area, and with the Maresme region, to the north of the metropolitan area). In contrast, for full dose, they corresponded to more rural areas (north and west on the map). In Table 1, it can be seen that the most economically disadvantaged ABSs (lower average net income per person; and higher unemployment, poor housing, and percentage of foreigners from countries with medium and low human development index) were the areas of agglomeration of deficiency cases. Conversely, these areas were those with the lowest proportion of people aged ≥65 years. ABSs with deficiency cases were the most densely populated at one dose, but were the least densely populated (i.e., rural areas) at full dose. Note that the economic inequality measured by the Gini index was practically the same in these areas as in other areas.

The results of the estimation of the joint model are shown in Tables 2, 3 and S3 (supplementary material).

In relation to the weekly cumulative percentage of vaccinated population, according to the doses received (Table 2), it can be seen that in all cases, this was influenced by socioeconomic variables. However, note that only for unemployment rate, poor housing and percentage of foreigners from countries with medium and low human development index, the credible intervals (CrI) did not contain unity in all cases.

In general, individuals in ABSs located in the upper two quartiles of average net income per person and in the lower two quartiles of unemployment rate (i.e., the least economically disadvantaged) had a higher propensity to be vaccinated than those in the most economically disadvantaged ABSs. In the same sense, the greater the percentage of the population aged ≥65 years in an ABS, the higher the propensity to be vaccinated, while ABSs located in the two upper quartiles of population density and areas with a high percentage of poor housing had a lower propensity to be vaccinated.

For unemployment rate and poor housing, a lower vaccination rate occurred with all vaccine doses; however, for average net income per person, there was no difference in the propensity to be vaccinated between the least disadvantaged and most disadvantaged ABSs for the booster dose, for population density with the full dose, or for the percentage of the population aged ≥65 years for one dose. Individuals in ABSs that were less unequal according to the Gini index (i.e., the first two quartiles) were more likely to be vaccinated with one dose, but less likely with the booster dose (there was no difference with the full dose). In addition, the higher the percentage of foreigners from countries with medium and low human development index in the ABS, the lower the propensity to be vaccinated for the full dose and the booster, but the greater for the first dose.

Regarding COVID-19 outcomes (Table 3), it can be seen that the more disadvantaged the ABS, the greater the risk of the occurrence of the outcomes, albeit with two exceptions. The more unequal an ABS according to the Gini index and the higher unemployment, the

Table 1

Descriptive statistics of the explanatory variables by the agglomerations of deficiency of cases of the smoothed rates of accumulated vaccination[a]. Sixth wave, from the first week of November 2021.

	One dose		Full dose	
	Deficiency (n = 112)	Other case (n = 261)	Deficiency (n = 14)	Other case (n = 359)
Average net income per person (€)				
mean (standard deviation)	11,994.3 (2209.2)	14,151.7 (3000.2)	12,585.1 (2615.6)	14,230.4 (3418.1)
median (Q1, Q3)	11,858.4 (10,816.2, 12,950.6)	13,560.8 (12,014.1, 15,612.1)	12,138.1 (11,069.1, 13,644.7)	13,712.0 (12,312.4, 15,359.0)
Gini index (%)				
mean (standard deviation)	31.18 (3.34)	30.73 (2.93)	30.88 (3.06)	30.67 (3.33)
median (Q1, Q3)	30.91 (28.29, 33.60)	30.39 (28.42, 32.41)	30.51 (28.43, 32.67)	30.29 (28.04, 31.97)
Unemployment rate (%)				
mean (standard deviation)	25.91 (5.14)	22.14 (3.68)	24.99 (4.99)	19.31 (3.17)
median (Q1, Q3)	25.74 (22.63, 28.91)	21.60 (20.02, 24.13)	24.47 (21.57, 27.97)	19.64 (17.13, 20.84)
Population aged 65 and over (%)				
mean (standard deviation)	18.33 (3.21)	20.61 (3.73)	18.83 (3.40)	23.69 (3.61)
median (Q1, Q3)	18.18 (16.23, 20.31)	20.56 (17.72, 23.28)	18.61 (16.62, 21.04)	24.33 (21.40, 25.97)
Poor housing (%)				
mean (standard deviation)	3.04 (2.63)	3.74 (5.36)	3.57 (4.77)	2.42 (2.38)
median (Q1, Q3)	1.96 (1.20, 4.09)	1.62 (0.99, 3.43)	1.70 (1.05, 3.76)	1.44 (1.09, 2.41)
Foreigners (%)				
mean (standard deviation)	12.07 (6.98)	8.90 (4.00)	11.27 (6.44)	7.02 (3.08)
median (Q1, Q3)	10.64 (7.29, 15.31)	8.72 (5.81, 11.39)	10.23 (6.76, 13.76)	6.96 (4.43, 8.88)
Population density (hab/km^2)				
mean (standard deviation)	2389.5 (3164.3)	1818.2 (3007.3)	1309.3 (2843.0)	2017.9 (3071.6)
median (Q1, Q3)	465.4 (18.6, 4427.7)	307.6 (36.7, 2396.9)	40.77 (23.8, 1979.8)	349.3 (40.2, 3107.4)

[a] Probability that the smoothed rates of accumulated vaccination were above the median of the cumulated percentage in each of the weeks, below 20 % (deficiency).

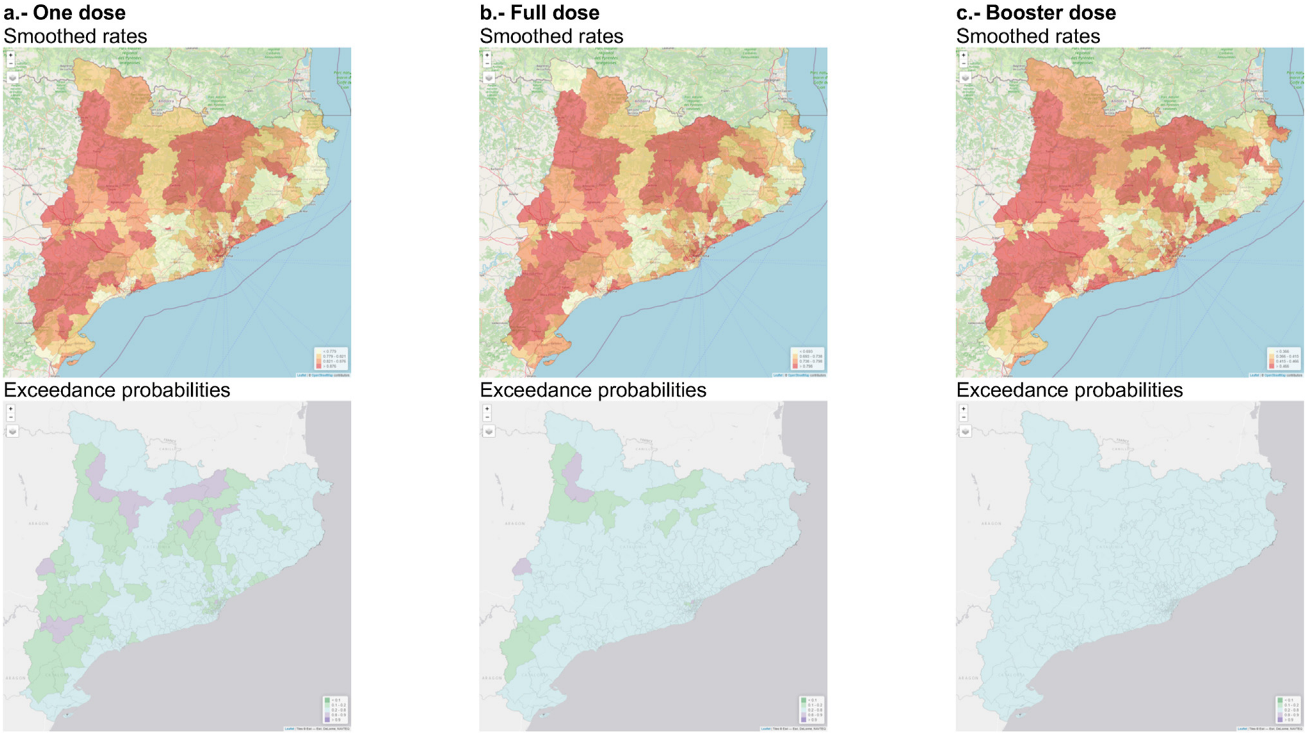

Fig. 1. Smoothed rates of cumulative vaccination. Sixth wave, from the first week of November 2021.

lower the risk of occurrence of the outcomes, particularly ICU admissions and deaths. Note, however, that for the Gini index, in incidence, and for unemployment rate, in hospitalisation, only in one of the quartiles did the CrI not contain unity (at 95 % in the Gini index and in 90 % in unemployment rate).

While COVID-19 outcomes did not influence the propensity to be vaccinated in the ABS (Table 2), it did influence the opposite (Table 3). In all cases, an increase in cumulative vaccination (in the last two weeks) implied a lower risk of occurrence of COVID-19 outcomes (1 % lower in incidence and around 10 % lower for the other outcomes).

Discussion

This study found that for all doses (one, full and booster dose), the weekly cumulative percentage of vaccinated population was influenced by socioeconomic variables. Individuals living in less economically disadvantaged ABSs had a higher propensity to be

Table 2
Results of the estimation of the joint model. Weekly cumulative percentage of vaccinated. Relative risks (95 % credible intervals).

	One dose	Full dose	Booster dose
Average net income per person greater than 12,178.40 € [Q1, Q2]	1.375 (0.933, 2.028)*	1.024 (1.005, 1.043)**	0.985(0.958, 1.012)
Gini index less than 30.51 [Q3, Q4]	1.508 (1.077, 2.111)**	0.996 (0.980, 1.012)	0.970(0.947, 0.994)**
Unemployment less than 24.14 % [Q3, Q4]	1.422 (1.177, 1.667)**	1.059 (1.040, 1.078)**	1.079(1.050, 1.108)**
Population density greater than 340.53 hab/km2 [Q1, Q2]	0.991 (0.938, 1.044)*	0.998 (0.980, 1.016)	0.953(0.928, 0.979)**
Poor housing (%)	0.881 (0.846, 0.918)**	0.998 (0.996, 1.000)*	0.998(0.995, 1.001)*
Population 65 years or over (%)	1.002 (0.955, 1.051)	1.014 (1.012, 1.017)**	1.027(1.023, 1.030)**
Foreigners (%)	1.042 (1.009, 1.076)**	0.993 (0.992, 0.995)**	0.988(0.986, 0.990)**
Cases in the last two weeks	1.000 (0.999, 1.000)	1.000 (0.999, 1.000)	1.000 (0.999, 1.000)
Hospitalisations in the last two weeks	1.000 (0.999, 1.000)	1.000 (0.999, 1.000)	1.000 (0.999, 1.000)
ICU admissions in the last two weeks	1.000 (0.999, 1.000)	1.000 (0.999, 1.000)	1.000 (0.999, 1.000)
Deaths in the last two weeks	1.000 (0.999, 1.000)	1.000 (0.999, 1.000)	1.000 (0.999, 1.000)

* The credible interval at 90% did not contain the unity. ** The credible interval at 95% did not contain the unity.
Reference categories between brackets. Models adjusted by individual heterogeneity (at Basic Health Area level), time trend and target population (as offset).

vaccinated, and the greater the percentage of the population aged ≥65 years, the greater the propensity to be vaccinated. These results are in line with findings from most previous published studies.[27–29]

In addition, results have been able to confirm the study hypotheses. First, inequalities in vaccination coverage varied in space (i.e., throughout the territory of Catalonia). In this sense, it was found that ABS with the highest vaccination coverage were in western Catalonia, and in the Barcelona metropolitan region in the east of Catalonia. On the contrary, and observing the exceedance probabilities, this study found that, for the first dose and the full dose, although to a lesser extent, the most rural and the most economically disadvantaged ABSs has coverage rates well below the median for all of Catalonia, even from November 2021 (sixth wave) [i.e., a very advanced phase of the vaccination campaign]. In the same sense, several other studies found spatial variability in the distribution of vaccination coverage, with higher vaccination rates in the higher socioeconomic status areas.[7–10,30]

Second, this study found that socioeconomic inequality in vaccination varied over time, although only for the full and booster doses. Specifically, inequalities in vaccination remained more or less unchanged until the fourth wave (March 2021), after which, ABS with higher income and that were less unequal had a higher propensity to be vaccinated. This increase over time in socioeconomic inequalities in COVID-19 vaccination was also found by other studies.[8,10,31]

Third, as evidenced by the maps, the variation over time of vaccination coverage was not the same throughout the territory (i.e. the space and time dimensions were not independent).

Finally, as reported in previous studies,[27,32,33] this study found that an increase in vaccination led to a lower risk of occurrence of COVID-19 outcomes (1 % lower in incidence and around 10 % lower for the other outcomes). However, the current study results showed that socioeconomic inequalities in COVID-19 outcomes did not decrease over time. For example, for ICU admissions, inequalities even increased in the sixth wave (starting in November 2021). Other studies have found that vaccination reduces socioeconomic COVID-19–related inequalities.[3,30] The current study found a similar result only for mortality, where vaccination reduced the rate (by around 10 %); however, this study did not find that, in this case, socioeconomic inequalities varied over time.

The current study is not free of limitations. First, the most important limitation was that an ecological design was used; therefore, the possibility of ecological fallacy and residual confounding bias should be considered. The study aimed to control for bias by including both a large number of observed confounders as well as random effects that captured unobserved confounders in the models. Second, some of the variables, particularly with regard

Table 3
Results of the estimation of the joint model. COVID-19 outcomes. Weekly cases. Relative risks (95 % credible intervals).

	Incidence	Hospitalization	ICU admission	Death
Average net income per person [Q1 <11, 116.20 €]				
Q2 11,116.20 € - 12,178.40 €	0.951 (0.932, 0.971)**	0.988 (0.972, 1.004)*	0.658 (0.571, 0.757)**	0.801 (0.658, 0.975)**
Q3 12,178.41 € - 13,683.07 €	1.005 (0.976, 1.035)	0.988 (0.971, 1.004)*	0.294 (0.083, 1.043)*	0.298 (0.054, 1.635)*
Q4 >13,683.97 €	0.924 (0.895, 0.955)**	0.993 (0.980, 1.005)	0.368 (0.104, 1.306)*	0.365 (0.066, 2.001)
Gini index [Q1 <28.43]				
Q2 28.43–30.51	1.004 (0.985, 1.023)	1.005 (0.989, 1.020)	0.823 (0.725, 0.934)**	0.748 (0.635, 0.879)**
Q3 30.52–32.61	0.967 (0.944, 0.992)**	0.985 (0.966, 1.004)*	0.043 (0.017, 0.109)**	0.013 (0.003, 0.047)**
Q4 >32.61	1.007 (0.981, 1.033)	0.991 (0.977, 1.004)*	0.039 (0.016, 0.098)**	0.012 (0.003, 0.042)**
Unemployment [Q1 <21.37 %]				
Q2 21.37 % - 24.14 %	0.929 (0.911, 0.947)**	0.985 (0.967, 1.003)*	1.091 (0.942, 1.263)	0.853 (0.681, 1.069)*
Q3 24.14 % - 27.78 %	0.877 (0.853, 0.902)**	0.993 (0.982, 1.005)	0.225 (0.050, 0.993)**	0.160 (0.022, 1.162)*
Q4 > 27.78 %	0.838 (0.812, 0.864)**	0.993 (0.981, 1.004)	0.286 (0.064, 1.266)*	0.163 (0.022, 1.190)*
Population density [Q1 <32.29 hab/km^2]				
Q2 32.29 hab/km^2-340.53 hab/km^2	1.022 (1.000, 1.043)*	1.002 (0.976, 1.028)	1.500 (1.298, 1.734)**	1.046 (0.819, 1.336)
Q3 350.44 hab/km^2-3012.68 hab/km^2	1.021 (0.992, 1,051)*	1.004 (0.993, 1.015)	12.548 (2.834, 56.380)**	66.031 (8.976,498.073)**
Q4 >3012.68 hab/km^2	1.029 (0.997, 1.062)*	1.006 (0.995, 1.017)	13.778 (3.109, 62.045)**	74.174 (10.153,552.131)**
Poor housing (%)	1.002 (0.999, 1.005)*	1.001 (0.993, 1.003)	1.625 (0.977, 2.710)*	1.905 (0.960, 3.794)*
Population 65 years or over (%)	1.005 (1.002, 1.008)**	1.001 (0.999, 1.004)*	1.253 (1.000, 1.253)*	1.413 (1.048, 1.907)**
Foreigners (%)	1.002 (0.999, 1.004)*	1.000 (0.999, 1.001)	1.109 (0.966, 1.274)*	1.155 (0.960, 1.392)*
Vaccination on the last two weeks				
One dose	0.999 (0.997, 1.003)	0.999 (0.999, 1.002)	0.999 (0.999, 1.001)	0.999 (0.999, 1.001)
Full dose	0.990 (0.890, 0.999)**	0.909 (0.829, 0.989)**	0.899 (0.819, 0.979)**	0.898 (0.817, 0.979)**
Booster dose	0.991 (0.893, 0.997)**	0.908 (0.830, 0.989)**	0.899 (0.818,0,0.979)**	0.897 (0.913, 0.982)**

* The credible interval at 90% did not contain the unity. ** The credible interval at 95% did not contain the unity.
Reference categories between brackets. Models adjusted by individual heterogeneity (at Basic Health Area level), time trend and target population (as offset).

to COVID-19 outcomes, could have been measured in error.[12] If the explanatory variables are measured with errors, the estimators will be inconsistent.[34] However, if the between-area variability of the variable measured with error is much greater than the within-area variability of such variable, then the effect of measurement error on the estimator consistency may be negligible.[35]

These limitations are offset by the strengths of this study. This is the first study to use a joint spatio-temporal model to assess the existence of socioeconomic inequalities in COVID-19 vaccination coverage, as well as to analyse the spatial variation over time of these socioeconomic inequalities. Models were used that controlled for a wide range of confounders, observed and unobserved, and for spatial and temporal dependence (i.e., for the spread of the inequalities in the territory and over time). The robustness of the study results to a different circumstance has been shown through sensitivity analyses. Finally, the study exclusively used open data.

In conclusion, areas with lower socioeconomic level had the lowest vaccination rates and the highest risk of COVID-19 outcomes. Higher vaccination rates reduced the risk of COVID-19 outcomes, while COVID-19 outcomes did not influence the likelihood of being vaccinated. The effects of the explanatory variables were not the same in all areas or between the different waves of the pandemic, and clusters of excess risk of low vaccination in the most disadvantaged areas were detected.

COVID-19 vaccination inequalities in the most disadvantaged areas could be a result of structural barriers, such as the lack of access to information about the vaccination process, and/or logistical challenges, such as the lack of transportation, limited Internet access or difficulty in scheduling appointments. Public health strategies should be developed to mitigate these barriers and reduce vaccination inequalities.

Author statements

Author contributions

MAB had the original idea for the article and designed the study. The bibliographic search and the writing of the introduction were carried out by all the authors. The methods and statistical analysis were chosen and performed by MAB and MS. XP created the tables and figures. All authors wrote the results and the discussion. The writing and final editing was done by all authors. All authors reviewed and approved the manuscript.

Acknowledgements

This study was carried out within the ‘Health Inequalities and COVID-19’ subprogram of CIBER of Epidemiology and Public Health (CIBERESP). We appreciate the comments of two anonymous reviewers of a previous version of this work who, without doubt, helped us to improve our work. The usual disclaimer applies.

Ethical approval

This was an ecological study with aggregate data (at the Basic Health Area level) and no individual-level data were used. In addition, all data were obtained from official sources in the form of open data with free access, thus no ethical approval was required.

Funding

This work was partially financed by the COVID-19 Competitive Grant Program (ID#61605991) from Pfizer Global Medical Grants, by the SUPERA COVID-19 Fund, from SAUN: Santander Universidades, CRUE and CSIC, and by the Consolidated research group 'Compositional and Spatial Data Analysis (COSDA)' 2021 SGR 01197, AGAUR, Government of Catalonia. The funding sources did not participate in the design or conduct of the study, the collection, management, analysis or interpretation of the data, or the preparation, review and approval of the manuscript.

Competing interests

None declared.

Data availability

We used open data with free access.
Code will be available at www.researchprojects.es.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.puhe.2023.11.024.

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