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How effective has the Spanish lockdown been to battle COVID-19? A spatial analysis of the coronavirus propagation across provinces

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fedea

Resumen no técnico

Contexto

Esta investigación se enmarca en la actual situación de alerta en la que se encuentra España, como consecuencia de la expansión explosiva que se ha observado recientemente de los casos de coronavirus en nuestro país. España reportó los primeros casos de contagio en febrero, importados principalmente de Italia. Rápidamente, la infección continuó propagándose hacia otras provincias españolas, lo que motivó la adopción de distintas medidas de distanciamiento, que culminaron con la declaración del estado de alarma del 14 de marzo de 2020. Con esta medida de control se pretendía evitar una tragedia aun mayor, a la vista del éxodo desde el epicentro de la epidemia hacia otras provincias que comenzó a observarse antes del estado de alarma.

Objetivo

El objetivo de este trabajo es analizar la efectividad de las medidas adoptadas para frenar la expansión de la epidemia o si, por el contrario, éstas debieron adelantarse en el tiempo, pese a afectar gravemente a la economía. El modelo espacial propuesto permite además conocer en qué medida la epidemia de COVID-19 de una provincia depende de la evolución de las epidemias de otras provincias.

Resultados

Nuestros resultados indican que una mayor población junto con un elevado número de personas de edad media y con estudios superiores contribuyen a adelantar la aparición de contagios. También obtenemos que el inicio, e intensidad, de las epidemias provinciales depende de la movilidad internacional, lo cual sugiere que las medidas de control de viajeros procedentes de zonas previamente afectadas, como es el caso de Italia, deberían haberse puesto en marcha mucho antes, en línea con las decisiones adoptadas en otros países.

Por otra parte, el estudio empírico realizado en este trabajo ha permitido confirmar que la declaración del estado de alarma del 14 de marzo ha logrado mitigar el efecto del contagio de forma muy significativa, si bien es cierto que tal reducción en el número de contagios difiere entre provincias. En general, las provincias que están más cerca de los principales epicentros del COVID-19 en España son las que más se han beneficiado de esta medida, ya que el estado de alarma ha permito romper el círculo vicioso de contagios entre provincias. En efecto, diferentes especificaciones de nuestro modelo indican que la movilidad de la gente entre provincias ha jugado también un papel significativo en la propagación del virus en España. Dicha fuente de propagación, sin embargo, se reduce significativamente una vez que se decreta el estado de alarma. Por lo tanto, dicha medida no sólo ha permitido contener los contagios dentro de las provincias sino además los contagios procedentes de otras provincias.

Según nuestras simulaciones, el número de casos confirmados en la España peninsular hubiera aumentado, en ausencia de estado de alarma, de 126 a 617 mil casos a fecha de 4 de abril de 2020. Con dicha medida, por tanto, se han evitado alrededor de 491 mil infecciones confirmadas, lo que representa una reducción media del 79.5% en el número de contagios potenciales. Sin embargo, nuestras simulaciones ponen también de manifiesto que se hubiera podido ahorrar un numero aun mayor de contagios y, por consiguiente de fallecimientos, si las medidas de control asociadas a la declaración de alarma se hubiesen puesto en marcha con sólo una semana de antelación. El número de casos confirmados hubiera pasado a 47 mil, menos de la mitad los confirmados a fecha de 4 de abril. Señalar finalmente que tal disminución hubiera evitado probablemente el colapso de muchos hospitales en nuestro país.

How effective has the Spanish lockdown been to battle COVID-19? A spatial analysis of the coronavirus propagation across provinces

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Abstract

This paper assesses the effectiveness of the Spanish lockdown of population on March 14th to battle the COVID-19 propagation, as well as the effect of bringing forward the date of this public intervention. We test not only whether the lockdown (and other control measures) has prevented local contagion of the virus, but also whether it has prevented the inter-province spread of COVID-19. We find a drastic reduction in the propagation of coronavirus across the Spanish provinces since March 14th, indicating that the lockdown has been quite effective in preventing the between-province spread of the coronavirus. Regarding the propagation of the virus within each province, we find a significant contraction in the rates of growth of coronavirus cases (5.8% on average) attributed to the lockdown. A first counterfactual exercise shows that the lockdown implemented on March 14 has reduced the number of potential COVID-19 cases by 79.5%. The largest reductions in coronavirus cases are found in provinces that are either close to the epicentres of the coronavirus or adjacent to provinces with more advanced epidemics. A second counterfactual exercise shows, however, that the number of coronavirus cases would have been reduced by an additional 12.8% if the lockdown had been brought forward to March 7th, a reduction that likely would have prevented the collapse of many hospitals in Spain.

Keywords: COVID-19, Spanish lockdown, spatial propagation.

JEL codes: I1, H840, Q54, R12.

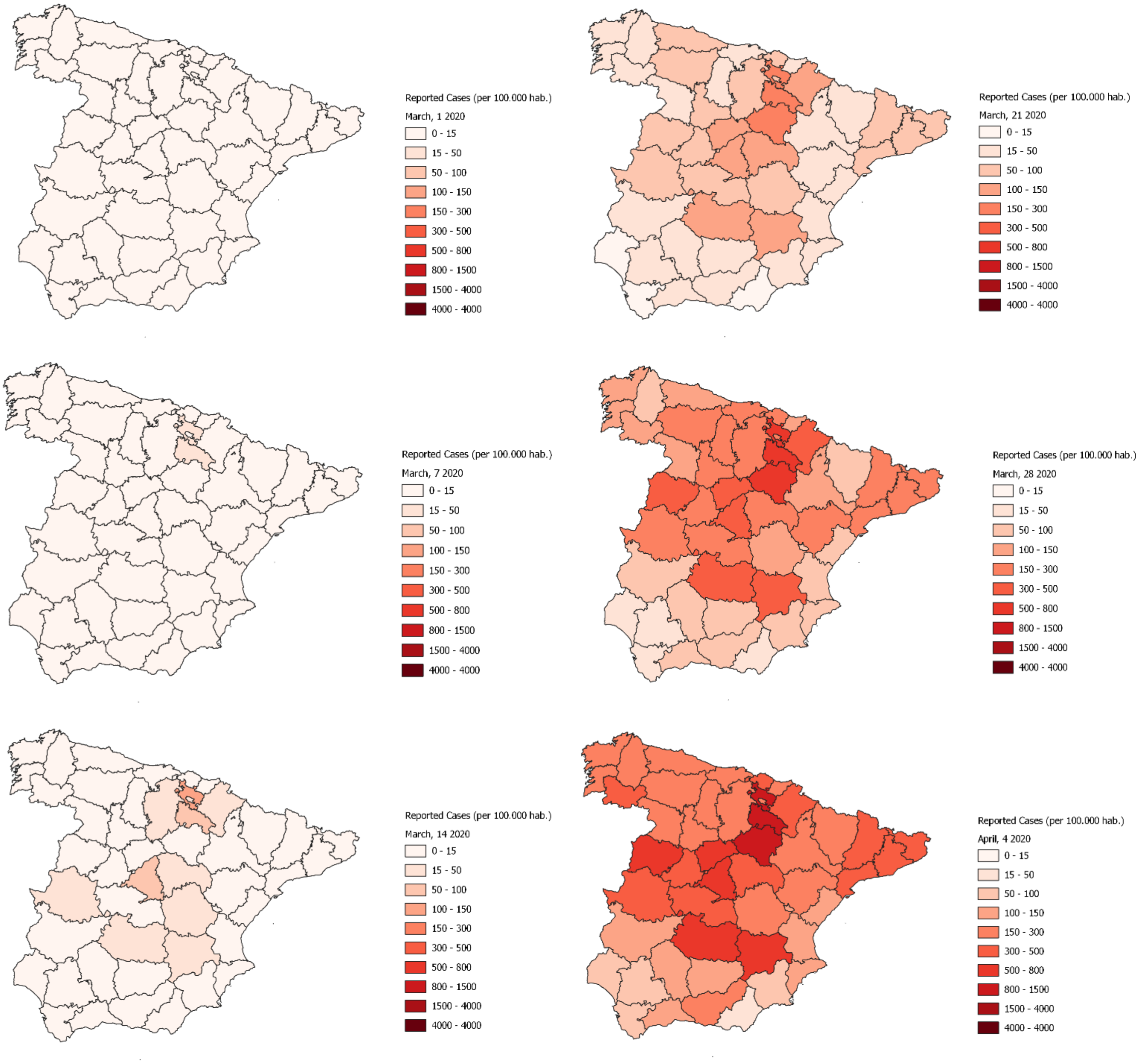
1. Introduction

An outbreak of a new coronavirus disease that causes respiratory tract infections that can be lethal in humans began in China in December 2019. The so-called coronavirus disease 2019 (COVID-19) spread rapidly to other countries. By late March 2020, the global death toll had passed 36,200, with infections rising to more than 755,500 (see BBC News, 2020). The global pandemic continues to grow despite the efforts to prevent the virus spreading, which in many countries include quarantines, case isolations, passenger travel bans, the cancellation and postponement of public events, social distancing guidelines and, most recently, national and regional lockdowns (see, e.g. Flaxman et al, 2020). The closures of schools and universities have affected a massive number of students, and the very tough measures implemented by many countries have led to severe global economic disruption affecting millions of workers.

The coronavirus pandemic is hitting Europe hard, especially Italy and Spain who had more than 100,000 and 86,000 cases of coronavirus respectively by 30th March. In Spain the first case was confirmed in the Canary Islands on January 31, and by the end of February multiple coronavirus cases related to the COVID-19 outbreak in Italy were confirmed. The virus spread rapidly to other provinces as shown in Figure 1. All Spanish provinces had already registered cases by the 14th of March. Social distancing was encouraged on 9th March and the schools were closed on the 13th of March to contain the outbreak. The Governments of Madrid, La Rioja and the Basque Country prohibited all in-class teaching in their regions in the following three days. Local outbreaks forced the Government of Cataluña to quarantine four Catalan municipalities on 12th March. The Spanish government declared a national lockdown of the population (or state of alarm) and prohibited public events on 14th March to battle coronavirus. All shops except pharmacies and stores selling basic necessities were forced to close. The Spanish authorities further tightened the lockdown by instructing non-essential workers to stay at home temporally and extending the lockdown until mid-April. Although the Spanish government decreed a national lockdown of population on March 14 to battle coronavirus, the epidemic continued to grow. For this reason, it is germane to assess the effectiveness of this dramatic public intervention as well as the impact of other (minor) control measures.

While the social distancing and self-isolation measures mainly aim to prevent local propagation of the virus within a neighbourhood, city or province, the lockdown also helps to prevent the propagation of COVID-19 across the Spanish provinces. In this sense, the Spanish lockdown was partially triggered by an exodus of students living in the epicentres of the Spanish coronavirus crisis that returned to their family towns once schools and universities began to suspend all face-to-face teaching and moved to online teaching and examinations. This “exodus” soared as rumours began circulating about an imminent nationwide lockdown to stop the coronavirus outbreak. The New York Times (2020) pointed out that in many European countries, including Spain, hordes of city residents decamped cities to spend their confinement in vacation homes, located in provinces that still did not have coronavirus cases or they were in the early stages of development of their coronavirus epidemics. Moreover, several Spanish newspapers (see, e.g. La Vanguardia, 2020) declared that thousands of citizens ignored the social distancing guidelines and travelled to protected natural areas or coastal vacation homes. While the locals of many of these coastal municipalities complied with the national lockdown and stayed at home, many non-locals stayed in public areas. Many inland and coastal municipalities were forced to close protected natural areas and beaches to prevent the influx of non-residents.

Figure 1. Geographical distribution of reported cases from March 1 to April 4, 2020



There is now a heated debate in Spain over whether the internal exodus to the provinces (often labelled as irresponsible) has markedly spread the virus across the country. Although individually this performance can be viewed as a natural human reaction, a general exodus from the main epicentres of the coronavirus crisis to less-populated provinces might have put local residents at greater risk as these provinces generally have few hospitals to handle a surge in patients and their populations tend to be older. Similar arguments can be made for the students who fled the Italian coronavirus outbreak in previous weeks, but in this case the external exodus from other countries (in particular, from China and Italy) casts doubts on the effectiveness of the Spanish coronavirus control measures, which did not impose either international passenger travel bans or screenings at airports and train stations until the Government of Spain decreed the cancellation of all direct flights from Italy to Spain on March 10.

This paper aims to shed some light on the above debates using a spatial econometric analysis of the Spanish coronavirus propagation. As it is also not clear whether the imported cases from Italy, and other countries, has played a relevant role in the onset of the coronavirus epidemics in Spain and their development, we first examine whether the onset of the epidemic in the Spanish provinces is correlated with a set of province-specific variables that somehow capture provinces' international connectivity.

We next carry out a second empirical exercise in order to test whether the national lockdown implemented on March 14th had a significant effect on the coronavirus patterns across provinces and over time. Our empirical model here aims to explain the daily evolution of the confirmed cases in the Spanish mainland provinces during the period between the onset of the epidemic in each province and the 4th of April. This model allows the development of the epidemic in one province to depend on the development of the epidemic in other provinces. Although our preferred model captures inter-province mobility in terms of provinces' proximity (contiguity), other spatial specifications were also used for robustness analyses, based on high-speed railway connection, students' regions of provenance, affective links between provinces, and tourist habits of city-residents. As most control measures began on the days of March 13th and 14th, we analyze data on coronavirus cases two weeks before and two weeks after those dates. We have used several sources in order to collect a dataset of coronavirus cases on a provincial basis that permits the use of spatial econometric techniques to capture spatial propagation effects across Spain.

We also carry out several counterfactual exercises to simulate what would have happened in two different hypothetical scenarios. We first try to predict the number of coronavirus cases if the lockdown of March 14th had not been implemented. This counterfactual analysis is similar to that carried out by Flaxman et al (2020). They forecasted deaths since the beginning of the epidemic up to and including the 31st of March, and find that, on average, 16 thousand deaths have been averted with the Spanish lockdown. This implies an estimated reduction in the number of potential deaths of about 67%.[1] Our counterfactual exercises will provide similar percentages for each province (region) in terms of coronavirus cases (deaths). The second counterfactual exercise tries to assess the effect of bringing forward the date of the Spanish lockdown one week, i.e. the effect of a hypothetical lockdown implemented on March 7th.

The related literature examining the COVID-19 epidemic is obviously scarce but evolving rapidly. We have already mentioned the study carried out by Flaxman et al (2020) using data from 11 European countries. Regarding the Chinese COVID-19 epidemic, Leung

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[1] This value has been computed by dividing 16000 deaths by 24000, i.e. the estimated deaths to 31 March assuming no interventions have occurred.

et al (2020) find, using a different approach to that used in the present paper, that a relaxation of the actual control measures in China would increase the cumulative number of COVID-19 cases, anticipating a possible second wave. This authors thus conclude that it should be necessary to monitoring the effects of relaxing control measures in terms of the increase of the new cases in order to readapt the decisions by policy makers. Gross et al. (2020) study the spatio-temporal propagation of the COVID-19 in China and compare it to other countries. They conclude that an early action may attenuate the disease, given the strong relation between population migration and the disease spreading. We also obtain a similar result but using more disaggregated data. Giuliani et al. (2020) also use data disaggregated by provinces to implement a model of epidemiology explaining the propagation of COVID-19 across the Italian provinces. These authors distinguish between propagation of the virus within a neighbourhood, city or province and propagation of COVID-19 across the Italian provinces. They refer to the first source of propagation as epidemic-within contagion, while the second source of contagion is referred to as epidemic-between contagion as it concerns the inter-province spread of COVID-19. The origin of such spatial dimension of propagation can be found in the high mobility of people across provinces. They conclude, using a similar empirical strategy to that used in our paper, that the control measures were more successful in those provinces in which there was an effective enforcement.

The added value of this study is the following. This is the first paper that examines the effectiveness of the control measures in Spain, and one of first papers in the recent literature that achieves this objective controlling for spatial propagation effects, an issue that is treated only marginally in the recent literature. Remarkable exceptions are Giuliani et al. (2020) and Gross et al (2020). While most of the previous literature is published in medicine-oriented journals and aims to estimate reproductive numbers, mortality and other epidemic features, we use more standard econometric techniques in economics to carry out our empirical exercise. We show that our empirical model somehow resembles the popular reproduction-based models used in previous literature. We also demonstrate, for instance, that a simple fixed-effect model with spatially-lagged variables is able to provide similar results as Flaxman et al (2020).

The paper is structured as follows. Section 2 summarizes the empirical strategy used in this paper to assess the effectiveness of massive public control measures implemented nationwide in Spain to contain the outbreak, controlling for (and measuring) expected propagation effects across the Spanish mainland provinces. Section 3 briefly describes the data used in the empirical analysis and its sources. Section 4 provides the parameter estimates and discusses the main results. Finally, Section 5 presents the conclusions.

2. Modelling lockdown impact and coronavirus propagation

This section develops a spatial model designed to measure the propagation of the coronavirus across the Spanish mainland provinces as well as to provide an assessment of the massive public control measures implemented nationwide to contain the outbreak. We also propose a very simple model to examine whether the beginning of the epidemic in each province is correlated with a set of province-specific variables.

Consider a panel of $i = 1, \dots, N$ provinces observed on $t = 1, \dots, T$ days. Let E_i denote the *onset date* of the epidemic, i.e. the date in which province i reports its first coronavirus case. We estimate a set of auxiliary regressions aiming at explaining E_i. If we use F_i to denote onset date determinants, the auxiliary regression to be estimated can then be written as follows:

$$E_i = \alpha + \beta F_i + \varepsilon_i \tag{1}$$

where ε_i is the traditional noise term capturing random shocks. This equation is estimated using the Ordinary Least Squares (OLS) estimator but with only N observations. This model is estimated using alternative onset date determinants in order to measure provinces' international connectivity. In our empirical application, we assume that the probability to travel abroad has to do with population, the proportion of middle-aged and highly-educated people, the number of Italian (Spanish) students in Spain (the EU), and the number of flight connections.[2] To examine whether the internal exodus has also contributed to the outbreak of the coronavirus, we also include number of holiday homes per capita as explanatory variable.

We then analyse the development of the epidemic in each province, i.e. the temporal evolution of coronavirus cases once each province reports its first coronavirus case. A key variable to carry out this analysis is the *epidemic time* $K_{it} = t - E_i$, which denotes the number of days relative to the onset date. We expect that the rate of growth of coronavirus cases varies with K_{it} as the traditional epidemic curve has a S-shaped form.

Let Y_{it} denote the accumulated number of confirmed (reported) coronavirus cases until day t in province i. As it is customary in panel data settings, we next assume that the number of cases in day t can be expressed as a function of the number of cases in a previous day as follows:

$$Y_{it} = \beta_{it} Y_{it-1} \tag{2}$$

where β_{it} can be interpreted as a heteroskedastic autoregressive parameter. For ease of notation, we have chosen a single temporal lag of Y_{it} to represent this relationship.[3] The key aim of the coronavirus control measures is to reduce β_{it}. This parameter thus plays the same role as the so-called reproductive number of the infection (R), a fundamental epidemiological quantity representing, in previous literate, the average number of infections per infected case over the course of their infection. If β_{it} is equal to one, there are no new infections and the epidemic has therefore been controlled. If β_{it} is greater than unity, new infections have been reported and the coronavirus epidemic is still spreading among the population despite the efforts to prevent the virus propagation.

In order to get a simple empirical specification of (2), we take natural logarithms and first-differentiate the model.[4] This yields the following expression:

$$lnY_{it} - lnY_{it-1} = ln\beta_{it} = e^{\alpha_i + \gamma Z_{it}} \tag{3}$$

where α_i is a set of province-specific but time-invariant fixed effects,[5] and $ln\beta_{it}$ is an exponential function of a set of covariates in order to impose the theoretical restriction $\beta_{it} \geq 1$.

In our non-spatial specifications of the model, the vector of covariates Z_{it} includes two sets of variables. First, Z_{it} includes a third-order function of lnK_{it} in order to capture the

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[2] The local conditions that determine the first centres of infections and the initial exposure to the risk of contagion are referred as endemic components by Giuliani et al (2020), according to terminology introduced in Paul and Held (2011).

[3] The model that describes the expected number of infections at time (day) t in Giuliani et al (2020) is also allowed to depend on the number of infections reported at time $t - 1$. We experimented with using longer temporal lags in our application but this resulted in less stationary series.

[4] We have found in our application that Y_{it} is not a stationary variable. Estimating (2) might thus give spurious results. This issue vanishes if we use rates of growth of reported coronavirus cases (or the logarithm of these growth rates).

[5] We expect that provinces' international connection not only have determined the onset of the outbreak but also has stimulated the propagation of the coronavirus. Using a second set of auxiliary regressions, we examine later on whether such fixed effects are correlated with the same determinants of onset dates.

temporal pattern of the virus epidemic. Second, Z_{it} includes a dummy variable $M14_t$ that takes the value 1 from the 14th of March, the day marking the imposition of most of the coronavirus control measures by the Spanish government. The coefficient of this variable allows us to test whether the Spanish lockdown has been able to attenuate the spread of the virus within each province. In this sense, our model specification looks like a Difference-in-Difference (DD) model where we compare an outcome variable after and before treatment (a policy measure), once we control for unobserved differences across units (provinces). As we do not have provinces that are never intervened, we try to simulate the *as if* scenario with no control measures using a parametric specification of the *epidemic* temporal effects. Our empirical strategy thus relies on the assumption that this parametric function is *mainly* estimated using pre-lockdown observations. Finally, we include one- and two-week lags of this dummy variable (i.e. $M21_t$ and $M28_t$) to capture larger effects attributed to the lockdown as time passes.[6]

Once a traditional noise term is added to (3), the model can be estimated using non-linear least squares (NLLS). However, we estimate this model *after* taking natural logarithms because the original (i.e. non-transformed) rates of growth of reported coronavirus cases do not follow a symmetric distribution. The logarithm transformation yields a symmetrically-distributed dependent variable.[7] This is an alternative empirical strategy if we take into account that the rates of growth in (3) are always non-negative due to the cumulative nature of Y_{it}. Once we take natural logarithms and a traditional noise term is added, the model that is finally estimated is linear, so it can be estimated using the standard Fixed-Effect (FE) estimator:

$$ln(lnY_{it} - lnY_{it-1}) = \alpha_i + \gamma Z_{it} + v_{it} \tag{4}$$

where v_{it} is a mean-zero error term capturing random shocks, measurement or specification errors, and other unobservable variables not correlated with the rates of growth determinants.[8]

To examine whether the internal exodus of students and city-residents from the main epicentres of the coronavirus outbreak to neighbouring and more distance provinces with close family and affective links has had a significant effect on the coronavirus epidemic in less-populated provinces, we use the following Spatial Lag Model (SLX) specification:

$$ln(lnY_{it} - lnY_{it-1}) = \alpha_i + \gamma Z_{it} + \lambda W_i X_t + v_{it} \tag{5}$$

where $X_t = (X_{1t}, X_{2t}, \dots, X_{Nt})$ is a $Nx1$ vector of explanatory variables of the Spanish provinces, and $W_i = (W_{i1}, W_{i2}, \dots, W_{iN})$ is a spatial weight vector where the weights ($W_{in} > 0,\ \forall i \neq n$) measures the degree of people mobility (connectivity) between provinces.[9] Finally, the λ parameter is the spatial autoregressive coefficient that measures the degree of spatial correlation between provinces. In our application, it can be interpreted as the propagation effect caused by the internal exodus of students and city residents. We expect to find statistically significant effects before the announcement of the Spanish lockdown. This effect should vanish after 14th March if the lockdown was effective.

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[6] This is also expected due to the gap between when a person gets infected and when he might subsequently infect another person, which is on average about six or seven days (see, Flaxman et al, 2020, p. 18).

[7] This can be clearly seen in Figure 2.

[8] Zero rates of growth often appear at the beginning of outbreaks as in this case our dependent variable looks like a count variable, a type of data in which the observations take a small range of non-negative integer values. Once the epidemic curve increases its slope, our dependent variable no longer has this feature. The customary procedure based on replacing the zero values with a tiny but positive number before taking logs tended to bias the initial temporal patterns. For this reason, we estimate (4) dropping the observations with zero rates of growth. We get very similar results if we estimate (4) with all epidemic observations and including a dummy variable controlling for (adjusted) zero values.

[9] By definition, $W_{ii} = 0$.

Inter-province mobility is captured using the spatial weight matrix $W = (W_1, \dots, W_N)$. This spatial matrix can be computed in different ways. The most popular is the so-called binary spatial weight vector where the weights equal one for adjacent units and zero for non-bordering units.[10] Given the different sources of coronavirus propagation, we compare the results using different specifications for W. The so-called W matrix is computed in terms of provinces' proximity (contiguity) in our preferred specification. Giuliani et al. (2020) also used a proximity criterium to estimate their propagation effects. Other spatial specifications were also used for robustness analysed, based on students' regions of origin, high-speed railway connectivity, and the tourist habits of city-residents and their regions of origin. The contiguity matrix is the most commonly used in spatial econometrics.

An alternative specification is the well-known Spatial Autoregressive model (SAR) that incorporates the spatial lag of the dependent variable instead the spatial lag of an explanatory variable.[11] There is no consensus over the most preferred specification (SLX vs. SAR) and whether the spillovers are local or global.[12] Vega and Elhorst (2015, p. 342) suggest taking the SLX model as point of departure, unless the researcher has an underlying theory or coherent economic argument pointing toward a different model. They show that the SLX specification is not only more flexible in modelling spatial spillover effects than other specifications but is also the simplest one. In this sense, LeSage (2014) states that most spatial spillovers are local in applied regional science modeling. Gibbons and Overman (2012) also show that the reduced forms of these two competing models are very similar if the W matrix is broadly defined.

We have selected the epidemic time of neighboring provinces (i.e. $X_{it} = lnK_{it}$) to capture the potential propagation effects between provinces for several reasons. First, this variable is exogenous by construction. In a SAR specification, X_{it} is replaced with (a transformation of) the dependent variable, which is endogenous, and thus should be instrumented as long as good instruments are available. Second, it is closely correlated with both the total number of coronavirus cases and its rate of growth. Thus, we do not need to choose between these two options. Finally, while it is true that we only take into account the evolution of the epidemic (age) of neighboring provinces, and not the impact of those epidemics in their population, it should be noted that such size effects are likely captured by our set of fixed effects.

Note finally that in our spatial specifications of the model, we interact $M14$ with $W_i lnK_t$ in order to test whether the lockdown has not only attenuated the within-province propagation of the virus but also the virus propagation between provinces. This interaction also allows the effectiveness of the lockdown to differ across provinces.

3. Sample and data

The empirical analysis is performed on a comprehensive dataset of Spanish provinces covering the period between the onset of the epidemic in each province and the 4th of April, constructed from several sources. Our empirical exercise aims to explain the daily evolution of

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[10] This matrix is often row-normalized in such a way the row elements of W sum the unity. The choice of a proper spatial weight matrix is contentious. For instance, Tiefelsdorf et al. (1999) point out that this standardization procedure may emphasize the prevalence of the spatial dependence on those units with fewer connections. In our application, this standardization procedure implies that between-province propagation depends on the average number of cases in neighbouring provinces, and not on the total number of nearby coronavirus cases. This might explain why we get poorer results using a row-normalized W matrix.

[11] For instance, Giuliani et al. (2020) seem to follow this approach although they do not use a standard spatial econometric model.

[12] A summary of the spatial economic and econometric literature can be found in Orea and Álvarez (2019).

laboratory-confirmed COVID-19 cases in the Spanish mainland provinces.[13] This data has been collected manually by the authors from the official press releases of the Spanish regional governments, the Ministry of Health and Wikipedia.

In particular, we had to consult these information sources to extend backwards the provincial data published by *Datadista* in GitHub under a free License since 13th March,[14] which extracts their data from a variety of documents published by the Ministry of Health. From the 28th March onwards we collected the data directly using *RTVE Flourish*, a tool that creates high-end maps and summaries the information of each province.[15] We used the regional online data released by the Ministry of Health to check the information provided by *Datadista* and *RTVE Flourish*.[16] We have also used the region-level data released by the Ministry of Health and the province-level dada released by the Spanish regional governments to correct typos and lack of information on coronavirus cases in some provinces (e.g. in Galicia). It should be noted that we were not able to get province-level data for the Cataluña region. For this reason, the whole region is treated as a single province.

Figure 2 shows the temporal evolution of reported coronavirus cases in each province. To better compare the provincial patterns, we depict the natural logarithm of reported cases in this figure. A feature worth highlighting is the relatively large dispersion of *onset dates* across provinces. This is a very important feature of our dataset because it allows two different empirical analyses to be carried out. While the first one is focused on the onset of the coronavirus epidemic in each province, the second analysis aims to explain the evolution of provincial epidemics and the effectiveness of the lockdown in reducing the number of reported cases. Moreover, this feature is crucial for the estimation of (4) because we need observations with both small and large epidemics to appropriately estimate the parametric function of lnK_{it}.

As mentioned previously, we do not directly try to explain (predict) the number of reported cases. Instead, we use the (natural logarithm of the) rates of growth of reported coronavirus cases to estimate (4) as we have found that this variable is stationary.[17] Figure 3 shows the box-plots of the rates of growth of reported cases by epidemic time. This figure clearly reveals two relevant features. First, the rates of growth of reported cases are much larger at the beginning of the epidemic than when the epidemic has advanced. That is, our dependent variable tends to decrease over the *epidemic* time. Second, the volatility is much larger when K_{it} is small and much smaller when K_{it} increases. This calls for using heteroskedasticity-robust standard errors when estimating our models.

Figure 4 shows the histograms of both $(lnY_{it} - lnY_{it-1})$ and $ln(lnY_{it} - lnY_{it-1})$. While the distribution of the rates of growth is highly asymmetric, their logarithm transformation follows a much more symmetric distribution. Although using the original or transformed rates of growth yield similar results, we use the logarithm transformation of the rates of growth because it can be estimated using the standard (linear) FE estimator.

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[13] Estimating the *true* number of COVID-19 cases presents challenges due to the high proportion of infections not detected by health systems, as pointed out by Flaxman et al (2020). Li (2020) shows that the undocumented or unobserved asymptomatic cases facilitate the rapid dissemination of this new coronavirus. Therefore, the reported case data might provide biased if we do not control for unobserved asymptomatic cases. We leave an examination of this issue for future research.

[14] See https://github.com/datadista/datasets/tree/master/COVID%2019.

[15] See https://app.flourish.studio/visualisation/1451263/.

[16] See https://covid19.isciii.es/.

[17] A Harris-Tzavalis (1999) unit-root test allows us to reject that both $(lnY_{it} - lnY_{it-1})$ and $ln(lnY_{it} - lnY_{it-1})$ contain unit roots, with a z-value equal to -84.9 and -31.1, respectively.

Figure 2. Temporal evolution of reported cases from March 1 to April 4, 2020

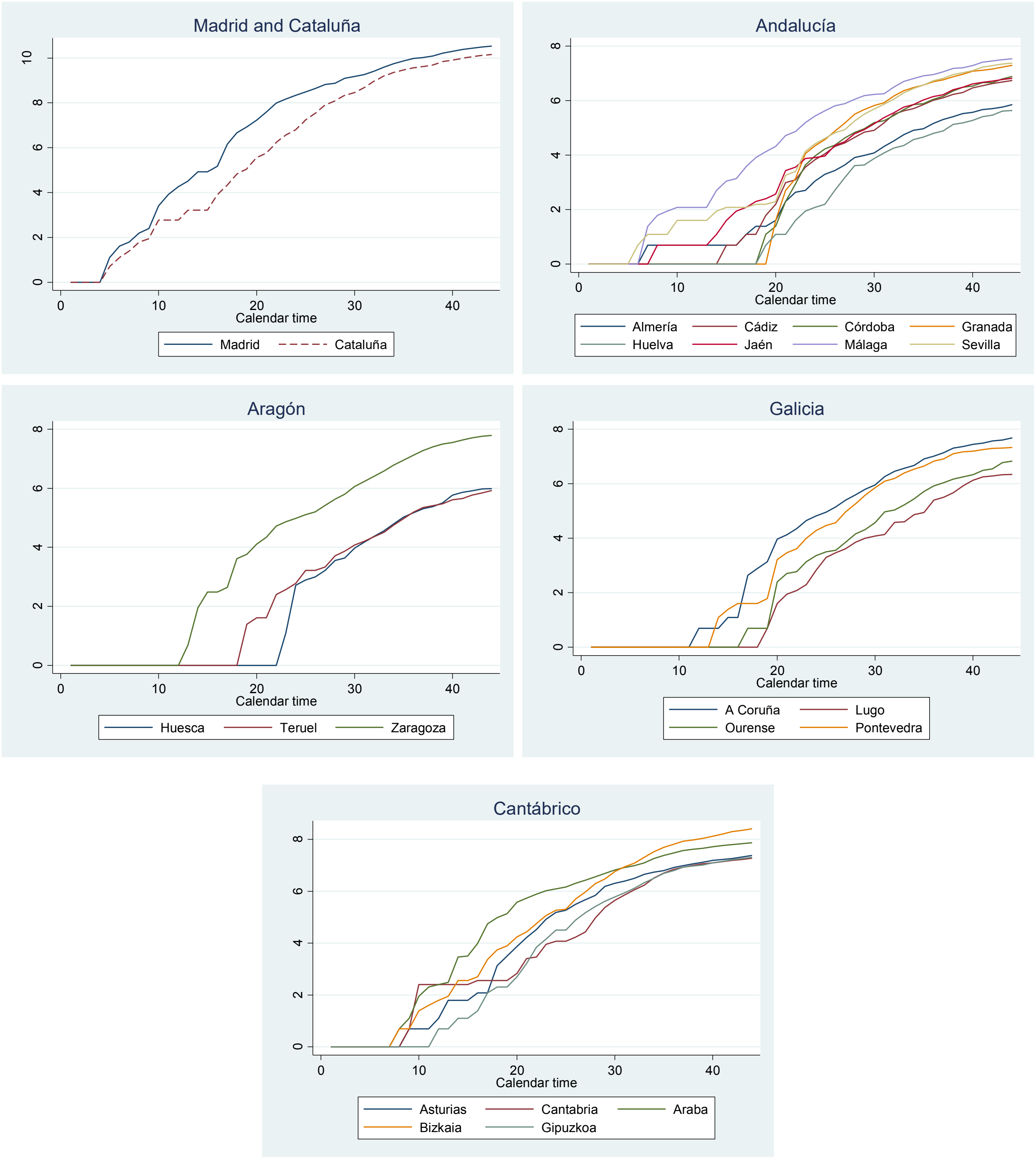


Figure 2. Temporal evolution of reported cases from March 1 to April 4, 2020 (Cont')

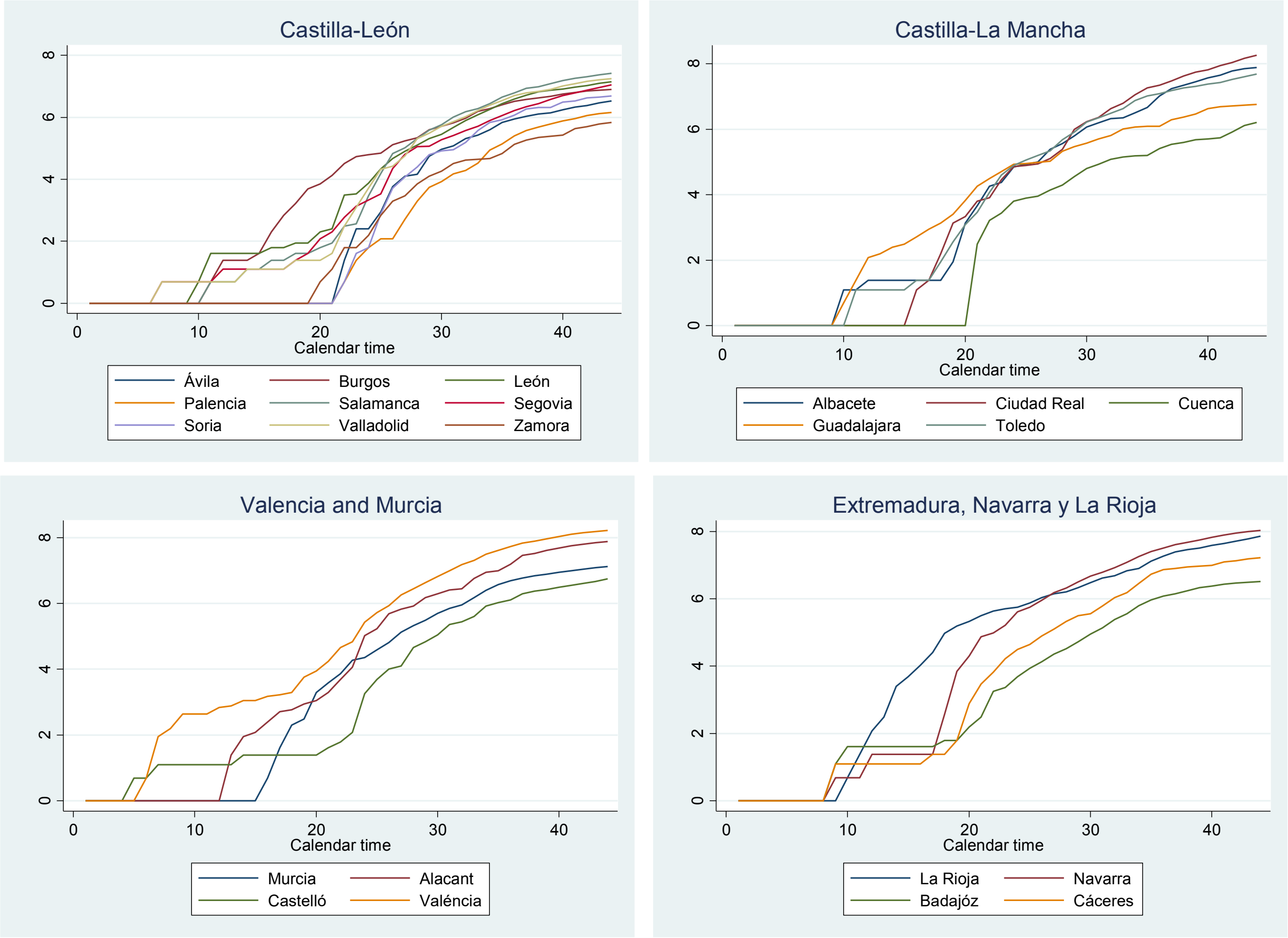


Figure 3. Rates of growth of reported COVID-19 cases

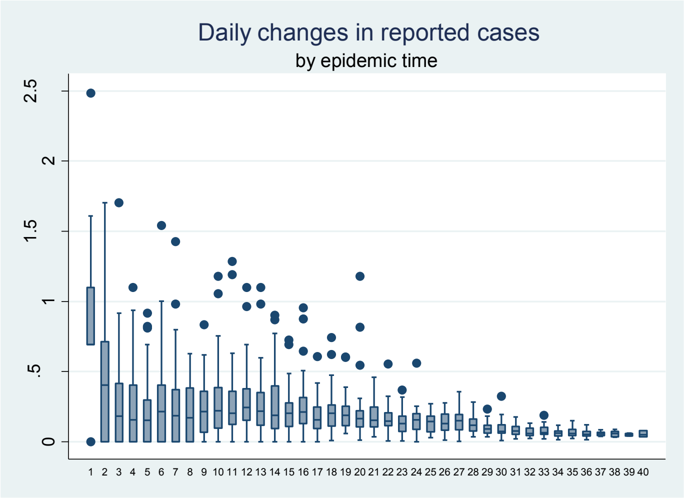
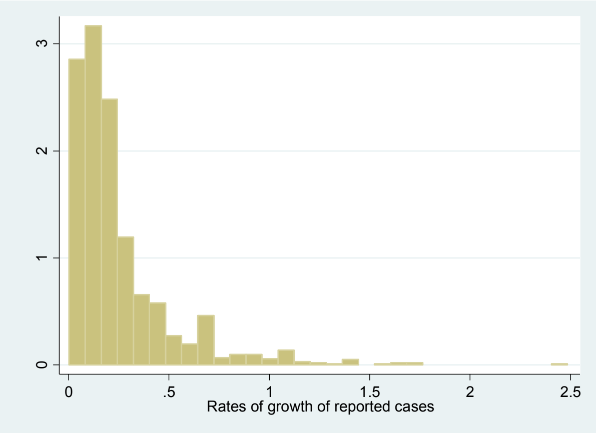
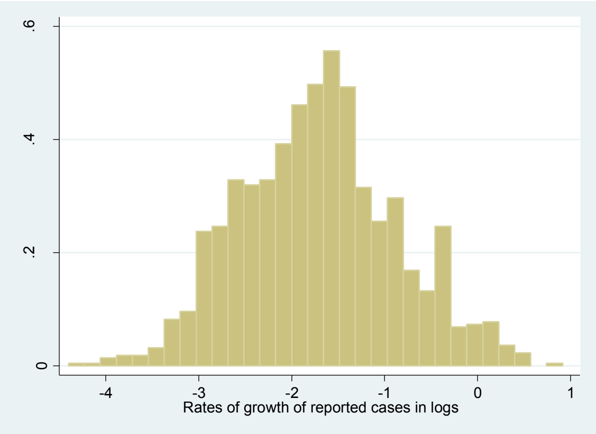


Figure 4. Histograms of alternative dependent variables

a) Rates of growth



b) Natural logarithms of rates of growth



We study the propagation of COVID-19 across the Spanish provinces, and in particular from the epicentre of the epidemic to the periphery, using the so-called W matrix which can be computed in terms of provinces' contiguity, students' regions of origin, and the tourist habits of city-residents and their regions of origin. We first compute the W matrix in terms of provinces' contiguity. It is standard in spatial economics to use physical proximity to measure spatial connectivity between units (provinces). In general, this literature confirms that the spillover effects emanating from adjacent territories represent the highest impact and are very similar to those obtained from the inverse of the distance (Álvarez et al., 2016).

We also consider that other relevant links may have contributed to expanding the virus from the epicentre to the periphery, such as affective links with city residents, mobility of students, transport connections and tourist habits. The main elements of these matrices can be summarized as follows. The W matrix based on regional affective links is a binary matrix in which the value 1 identifies the region with which a particular province has most affective links in terms of family provenance, place of birth, former holiday destination or former place of residence. INE provides this information from a questionnaire carried out by FAMILITUR (*Cuestionario de captación* 2004). The W matrix based on students' mobility represents the number of students enrolled in universities located in other provinces different than those where they did the University entrance exam (PAU) during the curse 2017-18. The information was provided by the Ministry of Education (*Datos y cifras del Sistema Universitario español*, 2018-19). The W matrix based on transport connections is computed using the connections between provinces via high-speed railway. This information is available for year 2018 from the Ministry of Transport (*Observatorio de ferrocarril en España. Informe 2018*). We compute a final W matrix using the main destination of residences in other provinces in year 2012. This information is provided by the Ministry of Industry, Trade and Tourism (*Movimientos turísticos de los españoles*, FAMILITUR).

Our onset-date auxiliary regressions are carried out using province-specific variables have been mostly been obtained from the Spanish National Institute of Statistics (INE, *Instituto Nacional de Estadística*). INE provides province-specific characteristics such as population by ages, population density, number of municipalities, and differences in sizes representing urban agglomeration and sectoral specialization, which are all available for 2019.[18] Additional province-specific variables are those representing educational levels and political orientation. The human capital is available at provincial level until 2013 and this dataset was developed by IVIE (*Instituto Valenciano de Investigaciones Económicas*).

We also consider in our auxiliary regressions a set of variables representing the external propagation effects from other countries. Data on national and international flights during the first months of 2020 in Spanish airports comes from the Ministry of Public Works. In addition, we obtain from the Ministry of Education the number of Italian students studying in universities located in Spanish provinces, and Spanish students that are studying in European universities during the academic year 2017-2018.[19] Finally, the number of secondary households (residences) is also gathered from INE. This data comes from the census of population and households of 2011. Although this data is not recent, it does allow us to identify those provinces with the largest number of potential visitors.

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[18] Some of these variables (e.g. urban agglomeration and sectoral specialization) have not been used in our preferred models as their coefficients were never significant.

[19] The last available report does not provide more recent data on students' mobility.

4. Empirical Results

4.1. Date of onset of COVID-19 epidemics

We begin this section by examining whether the onset of the epidemic in the Spanish provinces is correlated with a set of province-specific variables. Table 1 shows the parameter estimates of the *onset-date* auxiliary regression (1). As this equation is estimated using only 44 observations, we do not provide the results of a comprehensive model including all determinants of epidemic onsets. We instead provide sequential parameter estimates once a determinant is replaced with another one.

We first find that the coefficient of Population in Model 1 in Table 1 is negative and statistically significant. This result simply indicates that the coronavirus epidemic was initiated in the most-populated provinces earlier than the less-populated provinces. This is an expected result because more-populated provinces are much better connected with foreign countries, and thus they have a larger probability of importing cases of COVID-19 from abroad. To confirm this result, we replace this variable with a set of variables that correlated with provinces' international connections in Models 2-6. The probability of travelling abroad or of receiving visitors is likely to be related with the proportion of middle-aged and highly-educated people, the number of Italian (Spanish) students in Spain (the EU), and the number of flight connections. We again find that the coefficients of these variables are negative and statistically significant. These values confirm anecdotal evidence that one can find on internet (e.g. Wikipedia) that many epidemic onsets have to do with imported cases from other countries, and in particular from Italy, the European country that was the first and hardest-hit by coronavirus. The last model in Table 1 examines whether the internal exodus has also contributed to the outbreak of the coronavirus. The coefficient of holiday homes is positive and statistically significant. Therefore, we cannot state that the city-residents exodus has contributed to the onset of the coronavirus in other provinces.[20]

4.2 Lockdown impact on COVID-19 cases and coronavirus propagation

We next discuss the main results of this paper, which are obtained from the proposed spatial model (5). This is able to measure the propagation of the coronavirus across the Spanish mainland provinces in terms of reported cases as well as to provide an assessment of the Spanish lockdown (and other public control measures implemented around March 14) to contain the outbreak.

Table 2 shows the parameter estimates of several reported cases equations using different specifications for W. As the volatility of rates of growth of reported cases decreases as K_{it} increases, heteroskedasticity-robust standard errors are used to compute the t-statistics. The W matrix is computed in terms of provinces' contiguity, transport connection via high-speed railway, students' regions of origin, affective links between provinces, and tourist habits of city-residents. The largest goodness-of-fit is found when we use a simple contiguity W matrix to represent the propagation of the coronavirus across provinces. This is therefore our preferred model. Accordingly, the counterfactual simulations that are presented in the next section are carried out using the spatial model that, like in Giulani et al (2020), uses a proximity criterium to represent the propagation of the coronavirus across provinces.

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[20] The positive coefficient has likely to do with the fact that many of the provinces with more holiday homes per capita (e.g. Huesca, Zamora, Cuenca, Segovia, Soria, Ávila and Teruel) initiated their epidemic later than other provinces.

Table 1. Parameter estimates of onset-date auxiliary regressions

dep.var= onset date	Model 1			Model 2			Model 3			Model 4			Model 5			Model 6			Model 7		
	Coef.		t-stat	Coef.		t-stat	Coef.		t-stat	Coef.		t-stat	Coef.		t-stat	Coef.		t-stat	Coef.		t-stat
Intercept	14.094	***	15.09	134.7	***	3.73	20.870	***	8.91	14.390	***	12.19	14.869	***	12.28	14.289	***	13.97	8.370	***	6.52
Population	-0.002	***	-2.94																		
Middle-aged				-244.4	***	-3.38															
Higher education							-92.96	***	-3.74												
Italian students in Spain										-0.5646	**	-2.13									
Spanish students in EU													-0.370	***	-2.53						
Flights per capita																-1.396	***	-2.65			
Holiday homes																			32.66	***	3.94
R-squared	0.171			0.214			0.250			0.098			0.132			0.144			0.269		
Obs	44			44			44			44			44			44			44		

Notes:

*, **, *** indicate significance at the 10, 5, 1% level, respectively.

Population is measured here in natural logarithms.

Middle-aged is the proportion of middle-aged people.

Higher education is the proportion of highly educated persons.

The number of Italian students in Spain and the Spanish students in the EU have been normalized using the population in between 15 and 25 years old.

The flight figures and the number of holiday homes have been divided by total population.

Table 2. Parameter estimates of COVID-19 cases equations

Dep.var= ln(growth rate)	Contiguity		High Speed train		Students mobility		Emotional links		Tourist habits	
	Coef.	t-ratio	Coef.	t-ratio	Coef.	t-ratio	Coef.	t-ratio	Coef.	t-ratio
lnK	-1.142 ***	-6.12	-1.041 ***	-5.97	-1.118 ***	-6.28	-1.059 ***	-6.20	-1.062 ***	-6.16
$\ln K^2$	0.460 ***	3.64	0.407 ***	3.26	0.432 ***	3.48	0.407 ***	3.37	0.412 ***	3.42
$\ln K^3$	-0.101 ***	-3.88	-0.079 ***	-3.11	-0.082 ***	-3.31	-0.078 ***	-3.20	-0.085 ***	-3.49
WlnK	0.297 ***	3.96	0.096	1.49	0.238 ***	2.53	0.055	1.00	0.110 ***	2.29
M14	-0.122	-1.40	-0.141	-1.50	-0.126	-1.41	-0.155	-1.58	-0.150	-1.57
M21	-0.007	-0.12	-0.109	-1.55	-0.099	-1.43	-0.125	-1.70	-0.084	-1.18
M28	-0.320 ***	-4.59	-0.431 ***	-6.47	-0.424 ***	-6.29	-0.446 ***	-6.30	-0.401 ***	-5.86
WlnK·M14	-0.211 ***	-4.73	-0.048	-1.25	-0.202 ***	-3.25	-0.018	-0.67	-0.058 **	-2.22
Fixed Effects	Yes		Yes		Yes		Yes		Yes	
Average reduction	0.058		0.042		0.070		0.045		0.051	
R-squared	0.579		0.573		0.577		0.573		0.574	
Obs	1261		1261		1261		1261		1261	

Notes:

*, **, *** indicate significance at the 10, 5, 1% level, respectively.

Although all specifications of the W matrix provide similar results, it is worth mentioning that the spatial models based on student mobility and tourist habits find non-negligible propagation effects. Interestingly, the spatial model based on student mobility provides a larger average effect, 7%. It should be pointed out here that most of the undergraduate students coming from other provinces are enrolled in universities located in Madrid. This result thus seems to suggest that the exodus of students has had a significant effect in propagating the coronavirus epidemic to their provinces of origin.

All specifications provide very similar results, indicating that our empirical strategy is quite robust. The coefficients of the third-order function of lnK_{it} are all statistically significant. This is an expected result as the traditional epidemic curve is S-shaped and this form requires estimating up to a third-order function of the epidemic time. The average value of the province fixed effects (not shown) is 0.27, indicating that the initial rates of growth of coronavirus cases are relatively large, as Figure 3 suggests. The negative large coefficient of lnK_{it} indicates that these rates of growth decrease rapidly in the early stages of the epidemic, but the positive coefficient of lnK_{it}^2 indicates that the slope of the epidemic curves tends to flatten as the epidemic time passes.

A key result of our empirical exercise is the positive and statistically coefficient found for the spatially lagged variable, $W_i lnK_t$. This indicates that the rates of growth of COVID-19 cases in one province depends on the development of the epidemic in other provinces. In other words, two provinces with similar epidemic histories would evolve differently if one is close to one of the epicentres of the coronavirus in Spain and the other is far from some of these epicentres.[21] Therefore, this result provides evidence supporting the belief that the exodus of students and city residents did spread the virus across the country. Notice that we have interacted $M14$ with $W_i lnK_t$. This implies that the coefficient of $W_i lnK_t$ measures propagation effects *before* the implementation of the Spanish lockdown.

The coefficient of $W_i lnK_t \cdot M14$ is negative and statistically significant, indicating that the lockdown has attenuated the COVID-19 propagation between provinces. Moreover, we cannot reject that the combined effect of $W_i lnK_t$ and $W_i lnK_t \cdot M14$ is zero. This suggests that the lockdown has been quite effective in preventing the propagation of the coronavirus between provinces. Another issue is whether the lockdown has been effective to reduce the propagation of the virus within each province.

This within-province impact of the Spanish lockdown can be examined using the estimated coefficients of $M14_t$, $M21_t$ and $M28_t$. It should be mention here that $W_i lnK_t$ is currently measured in deviations with respect the sample mean. Therefore, the coefficient of $M14_t$ can be interpreted as a lockdown effect evaluated at the sample mean. We find negative but not statistically significant effects of $M14_t$ and $M21_t$ on the rates of growth of coronavirus cases. This is not a surprising result as the lockdown and other control measures (e.g. social distancing) require time to have an effect due to the gap in time between a person getting infected and subsequently infecting another person. It is worth highlighting, however, that the estimated coefficient of $M28_t$ is negative and statistically significant. The effects of the lockdown in Spain become significant two weeks after the implementation of the lockdown.

Taken together, the above results suggest that the lockdown has been effective in both preventing the propagation of the coronavirus between provinces and in attenuating the propagation of the virus within each province. We show the average effect of the lockdown at the bottom of Table 2. The reduction in rates of growth of coronavirus cases attributed to the

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[21] Gross et al (2020) find a strong correlation between the number of infected individuals in each province and the population migration from Hubei, the main epicentre of the Chinese epidemic, to this province.

lockdown is about 5.8% on average using our preferred specification. Notice however that $W_i lnK_t \cdot M14$ allows the effectiveness of the lockdown to differ across provinces. The negative effect found for this variable indicates that the lockdown tends to be more effective in provinces that are either close to the epicentres of the coronavirus or adjacent to provinces with more advanced epidemics. The reduction in rate of growth of coronavirus cases attributed to the lockdown in these provinces are much larger than the abovementioned average value.

For instance, we find remarkable effects in several provinces neighbouring Madrid, the hardest-hit Spanish province by coronavirus (e.g. 17% in Ávila, 10% in Segovia, and 13% in Cuenca). The lockdown has also had a remarkable effect in Valladolid (14.8%) because it neighbours Segovia and Salamanca, the latter being the main epicentre of the coronavirus in Castilla-León. We have also found large effects of the lockdown in Ciudad Real and Albacete (10% and 13.4% respectively), two adjacent provinces that are two epicentres of the coronavirus in the centre of Spain. In southern Spain, we find large effects in Córdoba (12.4%), which neighbours Málaga, the main epicentre of the coronavirus in this area. Four lowly-populated provinces have also had important effects: León (21%), which is adjacent to Ourense, the main epicentre in Galicia in terms coronavirus cases per capita; Soria (11%) and Palencia (9.6%) which neighbour La Rioja, one of the most important epicentres in the north of Spain; and Teruel (12.9%), which is adjacent to Cataluña, the second hardest-hit Spanish province by coronavirus. It is worth mentioning that the epidemic in many of these provinces (e.g. Teruel, Cuenca, Palencia, Soria, Ávila, Córdoba, Ciudad Real) began almost one week later than the epidemic in neighbouring provinces. In contrast, the reduction in rate of growth of coronavirus cases attributed to the lockdown were relatively low in three Andalusian provinces (0.3% in Almería, 2.9% in Cádiz and 2.6% in Málaga), Asturias (2.1%) and the two most-populated provinces in Galicia (0.4% in A Coruña, and 2% in Pontevedra).

To conclude this section, it is germane to mention that we have also regressed the estimated province fixed effects against the same set of covariates used to explain the onset of the epidemics in each province. The results are provided in Appendix A. We find that the most-populated provinces, [22] and provinces more strongly connected to foreign countries, have had more intensive coronavirus epidemics. Therefore, provinces' international connections have not only determined the onset of the outbreak but have also stimulated the propagation of the coronavirus within the provinces. We do not find the same effect for the variable measuring the relative importance of holiday homes.

4.3 Counterfactual exercises

We have carried out several counterfactual exercises using the parameter estimates of our preferred model to simulate what would have happened in two different hypothetical scenarios. We first predict the number of the number of coronavirus cases if the lockdown had not been implemented around March 14th. Our simulation exercise allows us to compute reductions in the number of coronavirus cases for each province, and not only for the whole country as in Flaxman et al (2020). Our model allows us to simulate coronavirus cases directly, not deaths attributed to this disease. However, deaths reductions can also be simulated indirectly if we use the percentage of coronavirus deaths published by the Ministry of Health for each Spanish region. The second counterfactual exercise tries to assess the effect of bringing forward the date of the Spanish lockdown one week. We simulate the effect of a hypothetical lockdown implemented on March 7th. That is, we examine what would have happened if the lockdown had been implemented at earlier stages of the coronavirus epidemic.

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[22] Gross et al (2020) also finds that the number of infected individuals in each province is a function of province population.

Table 3 provides the results of these two simulation exercises. As a benchmark, we first provide the cumulative number of cases of coronavirus reported in each province by April 4th, the time of writing of the present document. We next provide two counterfactual figures. The first one is the forecast of coronavirus cases that we would have observed on April 4th if the lockdown on March 14th had not been implemented. The second counterfactual is our forecast of coronavirus cases that would have been observed on April 4th if the lockdown had been implemented on March 7th. We finally provide the percentage difference between the reported and forecasted cases for each province. This variable measures the reductions of coronavirus cases attributed to the lockdown implemented on March 14th in the first simulation exercise. In the second simulation exercise, it measures additional reductions if the lockdown had been implemented one week before this date. Figure 5 compares the actual geographical distribution of coronavirus cases (shown in the middle map) with the counterfactual geographical distributions in the case of no intervention (bottom map) and in the case a hypothetical lockdown implemented on March 7th (top map).

The number of reported cases in the mainland Spanish provinces on April 4th was 126,859.[23] This number would have increased to 617,743 in the absence of lockdowns. Therefore, the lockdown implemented on March 14th has reduced the number of potential COVID-19 cases by 79.5%. This reduction is a bit larger than the 67% found by Flaxman et al (2020) in their study using country-level data. This is an expected result taking into account that our simulation involves a longer period and the gap between reported and forecasted cases increases exponentially over time. The largest reductions in coronavirus cases attributed to the Spanish lockdown are found again in provinces that are either close to the epicentres of the coronavirus or adjacent to provinces with more advanced epidemics, as the two last maps in Figure 5 suggest. The lockdown has been especially effective in many provinces of Castilla-León and Castilla-La Mancha, two regions adjacent to Madrid, and Zaragoza and Teruel, two provinces adjacent to Cataluña. In contrast, the lockdown has been much less effective in Almería (12.8%) and A Coruña (14.9), followed by several Mediterranean coastal provinces such as Murcia (48.8%) and Alicante (43.3%). The effect in three northern provinces are also relatively small (43.3% in Asturias, 40.2% in Pontevedra, 47.6% in Bizkaia and 50.2% in Gipuzkoa).

Table 4 shows the redactions in COVID-19 cases by regions. The total number of averted cases is 490,884. The lockdown has averted 119,577 cases in Madrid, the main epicentre of the Spanish epidemic, and more than 51,017 cases in Cataluña, the second hardest-hit province. It is noteworthy that the lockdown has averted more than 107,176 cases in Castilla-La Mancha, a much less populated region but with two local epicentres in Ciudad Real and Albacete. If we multiply the number of averted cases by the percentage of coronavirus deaths published by the Ministry of Health for each Spanish region, we can indirectly simulate the reduction in deaths attributed to the actual lockdown. The percentages used in this simulation are provided in Appendix B. 46,619 deaths have been averted with the actual lockdown in the Spanish Peninsula. The number of averted deaths stands out in Madrid (15,720), Castilla-La Mancha (11,272), Castilla-León (7,492) and Cataluña (5,168). Table 4 shows the reductions in Hospitalized cases and Intensive Care cases by regions. 220,531 hospitalized cases were averted with the lockdown. The lockdown prevented 25,757 persons being treated in the Intensive Care units of hospitals.

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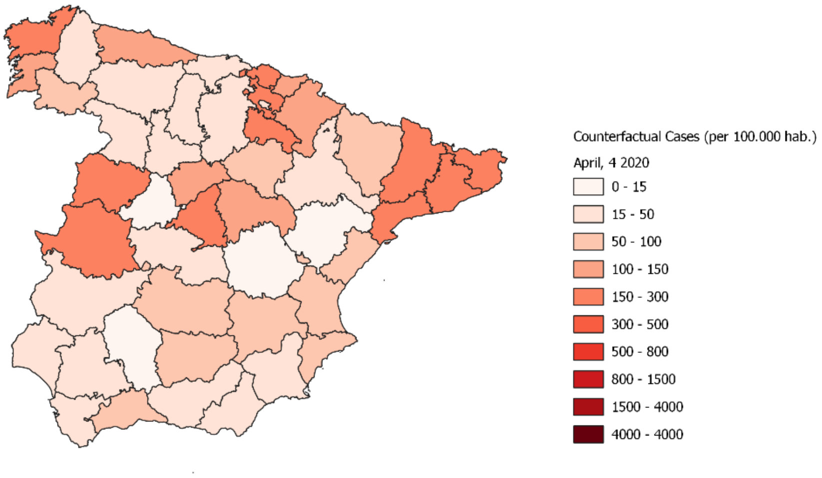
[23] This number does not coincide with the total number of cases in Spain because the Canary Islands, the Balearic Islands and the two autonomous cities (Ceuta and Melilla) are not included in our analysis. We have also found differences in the aggregated figures because some regions do not allocate all reported cases to one of their provinces if the infected person does not live in that region.

Table 3. Reported and simulated cases of coronavirus (April 4, 2020).

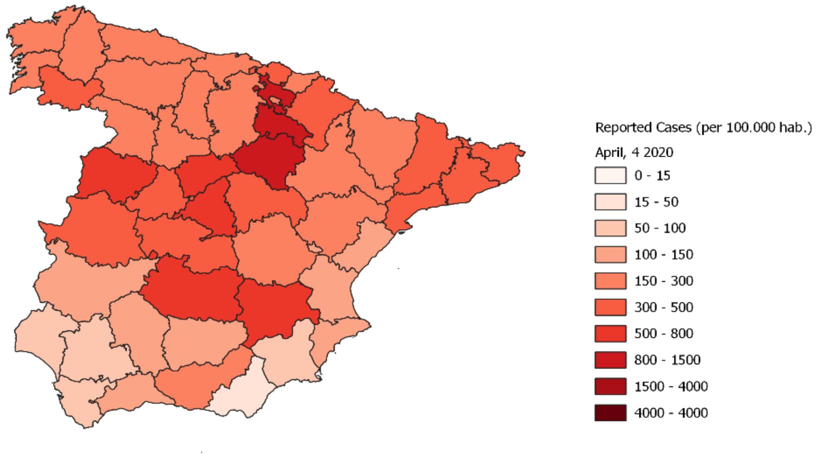
		Lockdown March 14			**Lockdown March 7**		
Region	Province	Reported	Counterfactual	Dif. (%)	Reported	Counterfactual	Dif. (%)
Andalucía	Almería	346	397	12.8	346	324	6.6
Andalucía	Cádiz	846	1684	49.8	846	454	46.4
Andalucía	Córdoba	974	11858	91.8	974	50	95.0
Andalucía	Granada	1477	9871	85.0	1477	148	90.1
Andalucía	Huelva	279	557	49.9	279	129	54.2
Andalucía	Jaén	914	2202	58.5	914	466	49.2
Andalucía	Málaga	1863	4057	54.1	1863	1051	43.7
Andalucía	Sevilla	1602	7507	78.7	1602	491	69.4
Aragón	Huesca	396	874	54.7	396	124	68.8
Aragón	Teruel	371	4521	91.8	371	17	95.8
Aragón	Zaragoza	2409	30447	92.1	2409	211	91.3
Asturias	Asturias	1605	2893	44.5	1605	1034	35.6
Cantabria	Cantabria	1441	12904	88.8	1441	210	85.5
CLM	Albacete	2653	47310	94.4	2653	207	92.2
CLM	Ciudad R.	3854	38921	90.1	3854	351	90.9
CLM	Cuenca	497	6750	92.6	497	14	97.3
CLM	Guadalajara	858	3394	74.7	858	273	68.2
CLM	Toledo	2169	20833	89.6	2169	307	85.9
Castilla-León	Ávila	679	11931	94.3	679	8	98.9
Castilla-León	Burgos	985	9102	89.2	985	138	86.0
Castilla-León	León	1261	15273	91.7	1261	134	89.5
Castilla-León	Palencia	472	2349	79.9	472	46	90.5
Castilla-León	Salamanca	1659	4634	64.2	1659	695	58.1
Castilla-León	Segovia	1148	10679	89.3	1148	194	83.2
Castilla-León	Soria	803	4976	83.9	803	53	93.5
Castilla-León	Valladolid	1403	26129	94.6	1403	125	91.1
Castilla-León	Zamora	339	1068	68.3	339	83	75.9
Cataluña	Cataluña	26032	77049	66.2	26032	12388	52.4
Extremadura	Badajoz	672	4999	86.6	672	121	82.1
Extremadura	Cáceres	1375	3940	65.1	1375	616	55.3
Galicia	A Coruña	2180	2563	14.9	2180	1976	9.4
Galicia	Lugo	565	2643	78.6	565	89	84.4
Galicia	Ourense	921	2712	66.0	921	287	69.0
Galicia	Pontevedra	1519	2539	40.2	1519	978	35.7
La Rioja	La Rioja	2592	9462	72.6	2592	869	66.5
Madrid	Madrid	37584	157161	76.1	37584	13678	63.6
Murcia	Murcia	1235	2392	48.4	1235	672	45.7
Navarra	Navarra	3073	15362	80.0	3073	867	71.8
País Vasco	Araba	2639	13295	80.2	2639	711	73.1
País Vasco	Bizkaia	4489	8560	47.6	4489	2764	38.4
País Vasco	Gipuzkoa	1500	3012	50.2	1500	837	44.2
Valencia	Alicante	2627	4636	43.3	2627	1593	39.4
Valencia	Castellón	852	1738	51.0	852	509	40.3
Valencia	Valencia	3701	12561	70.5	3701	1473	60.2
All		126859	617743	79.5	126859	47766	62.3

Figure 5. Geographical distribution of actual and simulated cases on April 4, 2020

a) Counterfactual cases if the lockdown were implemented on March 7, 2020



b) Actual cases with the lockdown implemented on March 14, 2020



c) Counterfactual cases with no lockdown

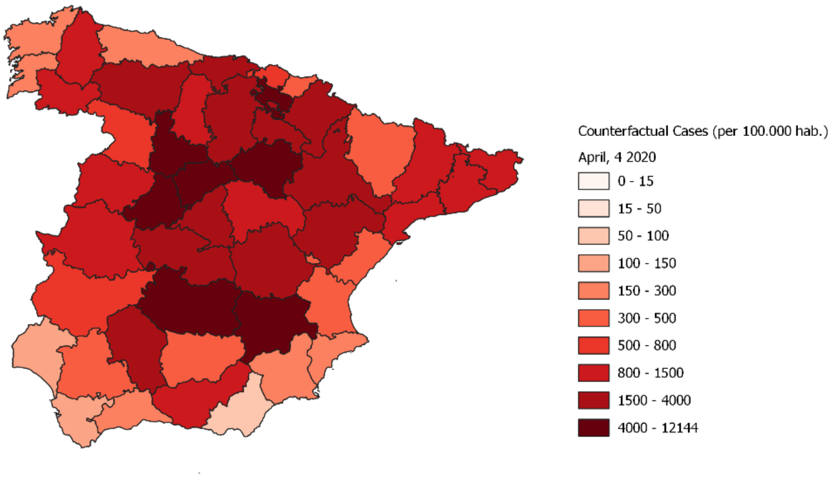


Table 4. Lockdown effects on hospitalized cases and deaths (April 4, 2020)

Region	RC	CC	AC		Reported cases (RC)				Counterfactual cases (CC)				Averted cases (AC)			
			Cases	%	Cases	H	IC	Deaths	Cases	H	IC	Deaths	Cases	H	IC	Deaths
Andalucía	8301	38132	29831	78.2	8301	4107	474	470	38132	18866	2177	2159	29831	14759	1703	1689
Aragón	3176	35842	32666	91.1	3176	1560	229	265	35842	17610	2584	2994	32666	16050	2355	2729
Asturias	1605	2893	1288	44.5	1605	808	90	80	2893	1457	162	144	1288	649	72	64
Cantabria	1441	12904	11463	88.8	1441	639	62	68	12904	5722	555	609	11463	5083	493	541
Castilla-La Mancha	10031	117207	107176	91.4	10031	2950	357	1055	117207	34469	4171	12327	107176	31519	3814	11272
Castilla-León	8749	86140	77391	89.8	8749	2574	351	847	86140	25343	3456	8339	77391	22769	3105	7492
Cataluña	26032	77049	51017	66.2	26032	18656	2249	2637	77049	55217	6657	7805	51017	36561	4408	5168
Extremadura	2047	8939	6892	77.1	2047	417	66	218	8939	1821	288	952	6892	1404	222	734
Galicia	5185	10456	5271	50.4	5185	1597	148	152	10456	3221	299	306	5271	1624	151	154
La Rioja	2592	9462	6870	72.6	2592	855	66	134	9462	3121	241	489	6870	2266	175	355
Madrid	37584	157161	119577	76.1	37584	14551	1499	4941	157161	60846	6268	20661	119577	46295	4769	15720
Murcia	1235	2392	1157	48.4	1235	447	80	59	2392	866	155	114	1157	419	75	55
Navarra	3073	15362	12289	80.0	3073	1399	123	178	15362	6994	615	890	12289	5595	492	712
País Vasco	8628	24867	16239	65.3	8628	4666	404	515	24867	13448	1164	1484	16239	8782	760	969
Valencia	7180	18935	11755	62.1	7180	1900	381	613	18935	5011	1004	1616	11755	3111	623	1003
All	126859	617743	490884	79.5	126859	56992	6656	12048	617743	277523	32413	58666	490884	220531	25757	46619

We next discuss what would have happened if the lockdown had begun on March 7th. The last three columns of Table 3 provide the results of this simulation exercise for each province. The two first maps in Figure 5 provide a spatial interpretation of delaying the lockdown from on March 7th to March 14th. If the lockdown had brought forward to March 7th, the number of coronavirus cases would have reduced by 62.3% in the Spanish Peninsula. The provinces that would have benefitted the most from an earlier lockdown belong to Castilla-La Mancha and Castilla-León, with reductions of more than 80%. Aragón also would have benefitted considerably from this intervention.

Taken together both counterfactual analyses, the lockdown implemented on March 7h has reduced the number of potential COVID-19 cases by 92.3%. As the lockdown implemented on March 14th has reduced the number of potential COVID-19 cases by 79.5%, the number of coronavirus cases would have been reduced by an additional 12.8% if the lockdown had been brought forward to March 7th. This reduction likely would have prevented the collapse of many hospitals in Spain because the number of cases would have dropped to 47,766 by April 4th, which is 2.5 times lower than 126,859, the reported number of cases for the set of provinces analysed in this paper.

5. Conclusions and discussion

Since multiple COVID-19 cases related to the coronavirus outbreak in Italy were confirmed in the Spanish Peninsula by the end of February, the virus spread rapidly to other provinces. Although the Spanish government, among other control measures, decreed a national lockdown of the population on March 14th to battle coronavirus, the epidemic continued to grow. In this paper we assess the effectiveness of this dramatic public intervention. Given the dramatic figures of coronavirus cases and deaths in Spain, we also assess the hypothetical effect of bringing forward the date of the Spanish lockdown.

While the social distancing and self-isolation measures mainly aim to prevent local propagation of the virus within a neighbourhood, city or province, the lockdown also helps to prevent the propagation of COVID-19 across the Spanish provinces. In this sense, the Spanish lockdown was partially triggered by an exodus of students and city-residents living in some of the epicentres of the Spanish coronavirus to their family towns or holiday homes. These were often located in much less-populated provinces that either did not have coronavirus cases yet or were in the early stages of development of their coronavirus epidemics. This paper aims to shed some light on this issue by estimating a spatial econometric model of the Spanish coronavirus propagation across provinces and over time. This model allows the development of the epidemic in one province to depend on the development of the epidemic in other provinces. It is also not clear whether the imported cases from Italy and other countries have played a relevant role in the onset of the coronavirus epidemics in Spain and their development. We try to measure external propagation effects from other countries using a set of variables that capture provinces' international connections.

The main findings of the paper are the following. We first examined whether the onset of the epidemic in the Spanish provinces is correlated with a set of province-specific variables. We find that the coronavirus epidemic was initiated in the most-populated provinces earlier than in the less-populated provinces. This is an expected result because more-populated provinces are much better connected with foreign countries, and many epidemic onsets have to do with imported cases from other countries, and in particular from Italy.

We link these results with other findings that are discussed in the paper regarding the number of confirmed cases and the impact of the Spanish lockdown. Using a second set of auxiliary regressions we find that the most-populated provinces and provinces more strongly connected to foreign countries have also more intensive coronavirus epidemics. Moreover, we find that the Spanish lockdown had a much larger impact in reducing the number of coronavirus cases when the epidemic onset dates are close to the intervention date. Taken together, these results suggest that larger efforts to prevent early importations of coronavirus cases from Italy and other European countries would have increased the effectiveness of the Spanish lockdown. In other words, the number of cases of coronavirus reported in many provinces, and hence their number of deaths, would have been much lower if passenger travel restrictions/bans, quarantine measures and screenings at airports and train stations had been implemented at the end of February.

The main results of this paper are obtained from a spatial model that is able to measure the propagation of the coronavirus across the Spanish provinces in terms of reported cases, as well as to provide an assessment of the Spanish lockdown to contain the outbreak. We find that the rate of growth of COVID-19 cases in one province depends on the development of the epidemic in other provinces. The origin of such spatial propagation can be found in the high mobility of people across provinces, in particular from provinces which are geographically close to each other. We also find epidemic-between contagion when our spatial model relies on student mobility and tourist habits. It should be pointed out here that most of the undergraduate students coming from other provinces are enrolled in universities located in Madrid. This result thus seems to suggest that the exodus of students has had a significant effect in propagating the coronavirus epidemic in their provenance provinces.

We also find a drastic reduction in the inter-province spread of COVID-19 since March 14th. This suggests that the lockdown has been quite effective in preventing the propagation of the coronavirus between provinces. Another issue is whether the lockdown has been effective in reducing the propagation of the virus within each province. In this regard, we find a significant contraction in the rates of growth of coronavirus cases (5.8% on average) attributed to the lockdown, but only after two weeks after the implementation of the lockdown. This is an expected result as the lockdown and other control measures (e.g. social distancing) require time to have an effect. Taken together, the above results suggest that the lockdown has been effective to both prevent the propagation of the coronavirus between provinces as well as to attenuate the propagation of the virus within each province. The lockdown has had a notable effect on the rates of growth of coronavirus cases in León (21%), Valladolid (14.8%), Albacete (13,4%), Teruel (12.9%), Córdoba (12,4%), Ciudad Real (10%), Soria (11%), and Palencia (9.6%). In contrast, the reduction in the rate of growth of coronavirus cases attributed to the lockdown were relatively low in Almería (0.3%), A Coruña (0.4%), Pontevedra (2%), Asturias (2.1%), Málaga (2.6%) and Cádiz (2.9%).

We carried out a counterfactual exercise to simulate what would have happened by April 4th if the lockdown had not been implemented around March 14th. Our results are in line with Flaxman et al (2020) using country-level data. We find that the lockdown implemented on March 14th has reduced the number of potential COVID-19 cases by 79.5%. This implies moving from 617,743 potential COVID-19 cases to the 126,859 reported cases by April 4th. The largest reductions in coronavirus cases attributed to the Spanish lockdown are again found in provinces that are either close to the epicentres of the coronavirus or adjacent to provinces with more advanced epidemics. The total number of averted cases is 490,884. Using the percentage of coronavirus deaths published by the Ministry of Health for each Spanish region, we estimate that 46,619 deaths, 220,531 hospitalized cases and 25,757 coronavirus patients in Intensive Care units have been averted with the actual lockdown on the Spanish Peninsula. A second counterfactual exercise was carried out to assess the effect of bringing forward the date of the Spanish lockdown by one week. If the lockdown had been brought forward to March 7th, we estimate that the number of coronavirus cases would have been reduced by 62.3%.

Taken together both counterfactual analyses, the number of coronavirus cases would have been reduced by an additional 12.8% if the lockdown had been implemented at earlier stages of the coronavirus epidemic, a reduction that likely would have prevented the collapse of many hospitals in Spain. Therefore, the general message of the paper is that the actual lockdown has been an effective tool to contain the COVID-19 outbreak in Spain. However, we feel that there was a lack of foresight on the part of the Spanish Government as it failed to anticipate the real development of the coronavirus epidemic in Spain.

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Conflict of Interest

Luis Orea and Inmaculada C. Álvarez declare that they have no conflict of interest.

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Appendix A

Parameter estimates of province-effect auxiliary regressions

dep.var= province effect	Model 1			Model 2			Model 3			Model 4			Model 5			Model 6			Model 7		
	Coef.		t-stat	Coef.		t-stat	Coef.		t-stat	Coef.		t-stat	Coef.		t-stat	Coef.		t-stat	Coef.		t-stat
Intercept	0.182	***	3.59	-4.0	*	-1.88	-0.123		-0.92	0.155	**	2.43	0.130	**	1.99	0.170	***	3.05	0.482	***	6.61
Population	0.000	***	3.16																		
Middle-aged				8.6	**	2.01															
Higher education							4.42	***	3.10												
Italian students in Spain										0.036	**	2.52									
Spanish students in EU													0.023	***	2.87						
Flights per capita																0.082	***	2.88			
Holiday homes																			-1.64	***	-3.48
R-squared	0.192			0.088			0.187			0.131			0.164			0.165			0.224		
Obs	44			44			44			44			44			44			44		

Notes:
*, **, *** indicate significance at the 10, 5, 1% level, respectively.
Population is measured here in natural logarithms.
Middle-aged is the proportion of middle-aged people.
Higher education is the proportion of highly educated persons.
The number of Italian students in Spain and the Spanish students in the EU have been normalized using the population in between 15 and 25 years old.
The flight figures and the number of holiday homes have been divided by total population.

Appendix B

Confirmed and treated coronavirus cases and deaths by regions in April 4, 2020

Region	Reported cases	Hospitalized	Intensive Care	Deaths	Hospitalized (%)	Intensive Care (%)	Deaths (%)
Andalucía	8301	4107	474	470	49.5	5.7	5.7
Aragón	3232	1588	233	270	49.1	7.2	8.4
Asturias	1605	808	90	80	50.3	5.6	5.0
Cantabria	1441	639	62	68	44.3	4.3	4.7
Castilla-La Mancha	10031	2950	357	1055	29.4	3.6	10.5
Castilla-León	8749	2574	351	847	29.4	4.0	9.7
Cataluña	26032	18656	2249	2637	71.7	8.6	10.1
Extremadura	2047	417	66	218	20.4	3.2	10.6
Galicia	5944	1831	170	174	30.8	2.9	2.9
La Rioja	2592	855	66	134	33.0	2.5	5.2
Madrid	37584	14551	1499	4941	38.7	4.0	13.1
Murcia	1235	447	80	59	36.2	6.5	4.8
Navarra	3073	1399	123	178	45.5	4.0	5.8
País Vasco	8628	4666	404	515	54.1	4.7	6.0
Valencia	7184	1901	381	613	26.5	5.3	8.5

Source: Spanish Ministry of Health

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