Modeling the spatiotemporal epidemic spreading of COVID-19 and the impact of mobility and social distancing interventions

Supplemental material

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S1. EPIDEMIC SCENARIOS

Apart from capturing the past course of a real pandemic and forecasting its future evolution, the framework here presented constitutes an useful tool for evaluating different interventions of interest for policy making. In this regard, the complexity of the equations governing the evolution of an age-stratified metapopulation, allows for incorporating realistic interventions and assessing their performance in reducing the impact of the disease over the population. Taking advantage of this possibility, we now study four different scenarios: the constraint of the inter-territorial mobility, the closure of the epicenter of the pandemic in Spain, and the selective confinement to elderly and young population and the extension of the strict lockdown regime.

A. Constraining mobility among provinces

First, we aim at modifying the morphology of the mobility network to unveil the role that human flows over different territories have played in fostering the spread of COVID-19. In particular, we are interested in revealing the relevance of the mobility network for the dissemination of the first cases in Spain until lockdown was enforced.

For this purpose, we compare the evolution of the spatial diffusion of COVID-19 with the picture provided by an alternative scenario in which the mobility between provinces (the administrative division of Comunidades Autónomas in Spain) is forbidden since the beginning of the disease. In mathematical terms, this policy is reflected in the mobility network by turning every flow connecting different provinces into self-loops, so that the population following these mobility paths stay inside their municipality. It is important to stress that this mobility restriction does not imply any kind of household confinement.

Figure S1 shows the distribution across Spain's territory of the municipalities with more than 10 cases as of March 15 when no mobility restriction is at work (left) and when the inter-provincial mobility is blocked (right). The maps in this figure clearly reveal the relevance of inter-provincial mobility at the early stages of the disease. In particular, we check that those connections disseminated the initial infectious seeds across more municipalities, thus making more difficult to concentrate efforts to fight local outbreaks.

B. Closing the epicenter of the pandemic

Madrid became the epicenter of the pandemic during the first epidemic wave in Spain. The international connectivity facilitating the arrival of imported cases along with a massive community transmission driven by the high population density existing in Madrid lead to the rapid unfolding of COVID-19 epidemics there. In the presence of clear epidemic centers, one typically discussed intervention consists in isolating these zones from the rest of the territory. To have quantitative information about the impact of such intervention, we remove the flows in the mobility network involving Madrid and analyze the course of the disease.

In Fig. S2 we represent the time evolution of the relative difference number of cases when Madrid is isolated with its corresponding to the original mobility network. Positive values indicate a beneficial effect of the policy whereas negative values encode a detrimental impact of Madrid closure. Overall, restricting Madrid mobility has a positive impact in the course of the epidemic. Nonetheless, note that the effect of the geographical closure of the most affected areas is not very pronounced, for it should be combined with strong local control policies implemented inside them to efficiently control the outbreak.

C. Selective confinement of non-active population

A crucial factor to understand the disparate COVID-19 numbers across similar countries is the timeliness of

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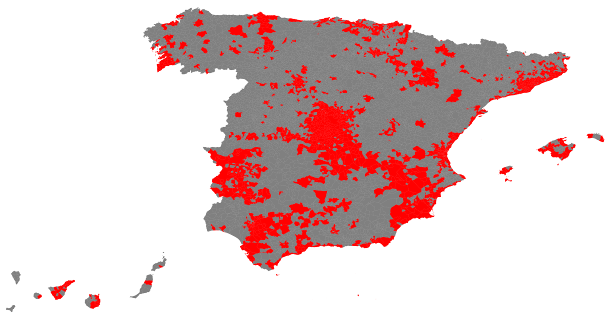

Figure S1. Spatial distribution of COVID-19 cases according to two different underlying mobility networks: the original one, estimated from INE data (left) and a new one where mobility between different provinces is removed (right). In both panels, red colored areas correspond to municipalities with more than 10 reported cases by March 15.

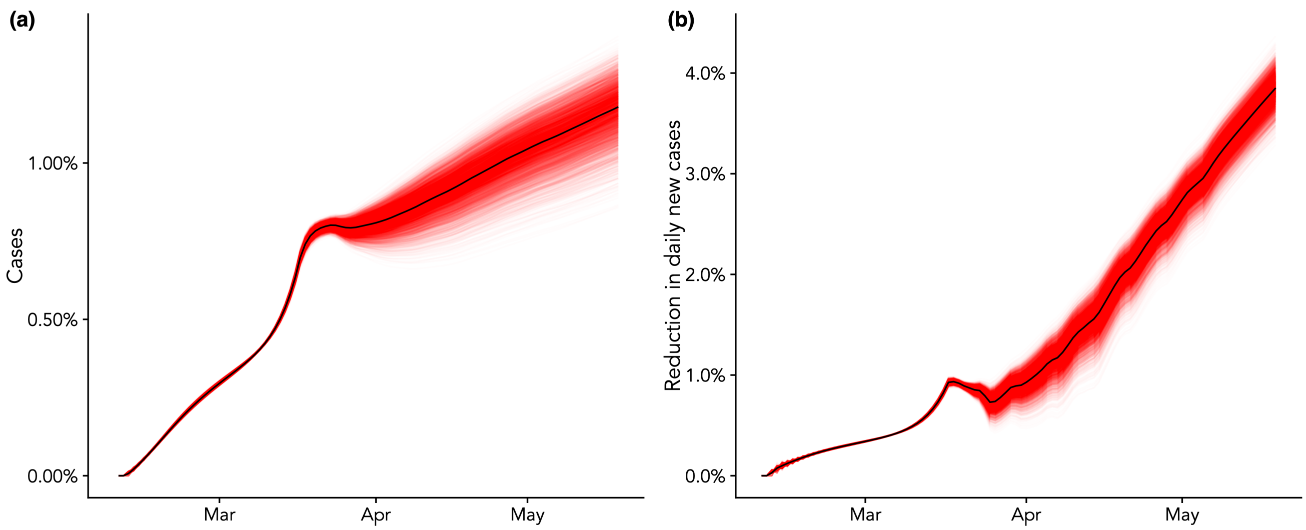

Figure S2. Time evolution of the relative reduction in the cumulative number of cases (a) and new daily cases (b) in an epidemic scenario where Madrid is isolated from the rest of Spain. This is achieved by removing those flows connecting Madrid with different regions in the mobility network.

the policies promoted to keep its propagation under control. One typical example can be found in Europe during the first epidemic wave: while countries such as Austria or Portugal deployed early interventions, thus alleviating the impact of COVID-19, other countries such as Spain or Italy acted late when the disease was already widespread across their territories. In this sense, the fear of dismantling the socio-economic fabric of the countries when isolating the active population constitutes one of the most important conditioning factor preventing these countries from acting earlier.

In light of this problem, one alternative intervention, aimed at keeping most of the country functionality and improving the control of the epidemic, would have been to enforce an early selective confinement of the non-active population. To capture this intervention in our formalism, we restrict the contacts of the young and elderly population to those taking place inside their households at a given time $t_{c'}$ before the state of emergency was declared in Spain (March 14, 2020). After this day, the lockdown of young and elderly patterns is again coupled to the one of the active population.

In Fig. S3 we illustrate the huge benefit of cutting possible transmission chains by performing timely selective confinements at the early stages of the disease, i.e., when the number of cases grows exponentially. In particular the results are obtained when this age-selective confinement is applied on February 28.

D. Extension of strict lockdown period

Finally, we address the benefits of prolonging the second lockdown period in Spain when every activity with

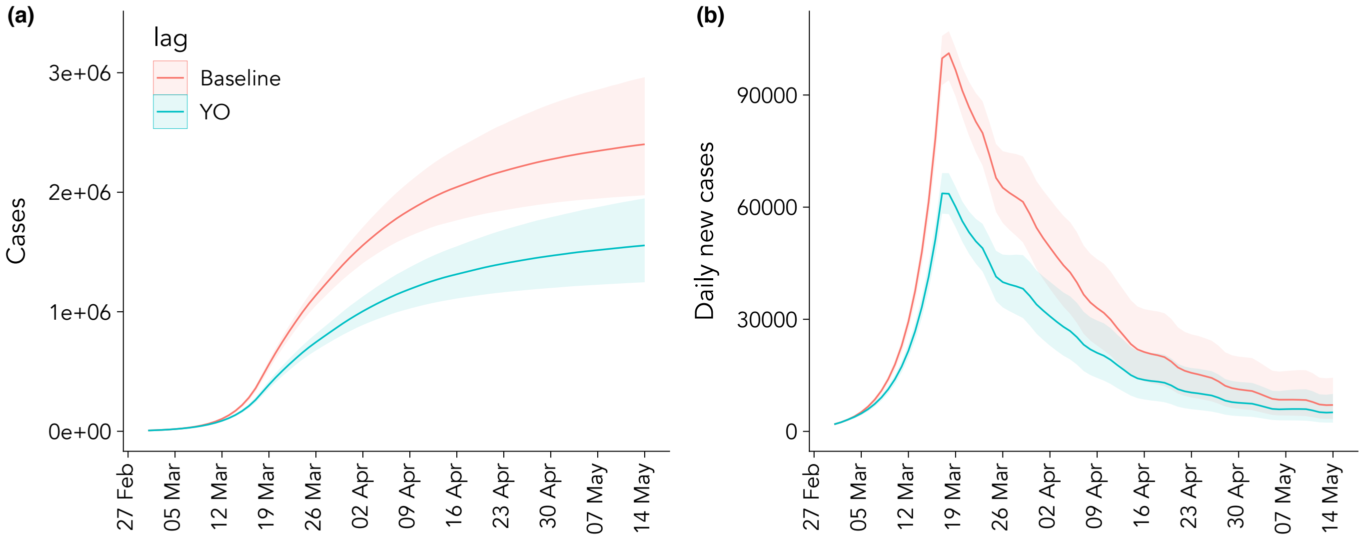

Figure S3. Effect of enforcing a selective confinement to non-active population (see text for details) on the course of the pandemic in Spain. The course is characterized by the time evolution of the cumulative number of cases (a) and new daily cases (b) for both the baseline and the intervened (YO) scenarios. Colored ribbons cover a 95% prediction interval.

Scenarios	Cases	Daily new cases
Real	[2,060,526 - 3,347,466]	[2,720 - 19,273]
1 week	[2,037,360 - 3,175,669]	[1,700 - 11,731]
2 weeks	[1,994,002 - 3,047,854]	[968 - 6,845]
4 weeks	[1,977,928 - 2,970,631]	[449 - 3,437]

Table S1. Predictive interval on the number of cases and daily new cases for the different scenarios considered in Fig. S4.

the exception of essential services was banned (EM window in Fig. 2 of the main text). For this purpose, we depict the evolution of the number of cases and daily new cases under the observed mobility and when increasing the duration of the EM lockdown. To do so, we extend the time series $\{\kappa_0(t)\}$ characterizing the evolution of the mobility reduction over the EM lockdown (see Fig. 3 of the main text) during three different periods: 1 week, 2 weeks or 4 weeks. In each of the three cases, after the extra lockdown window, the evolution of the mobility is kept as it was observed after the original EM period. The predictions show a reduction in both metrics as we increase the weeks of lockdown, showing a clear decreasing trend in the number of daily new cases on the most restrictive scenario. Remarkably, simulations also show considerable shrinking of the uncertainty range for daily new cases as we add weeks to the confinement policy, see Table S1 and Fig. S4. Namely, the upper bound goes from 19,273 daily new cases for the real scenario to just 3,437 for the four-week lockdown extension scenario. Although a complete stop of the spreading is almost impossible to achieve without a vaccine or clinical treatment, reducing the incidence to a manageable value through an extension on the lockdown duration could have had an essential role in mitigating, or at least delaying the current second wave.

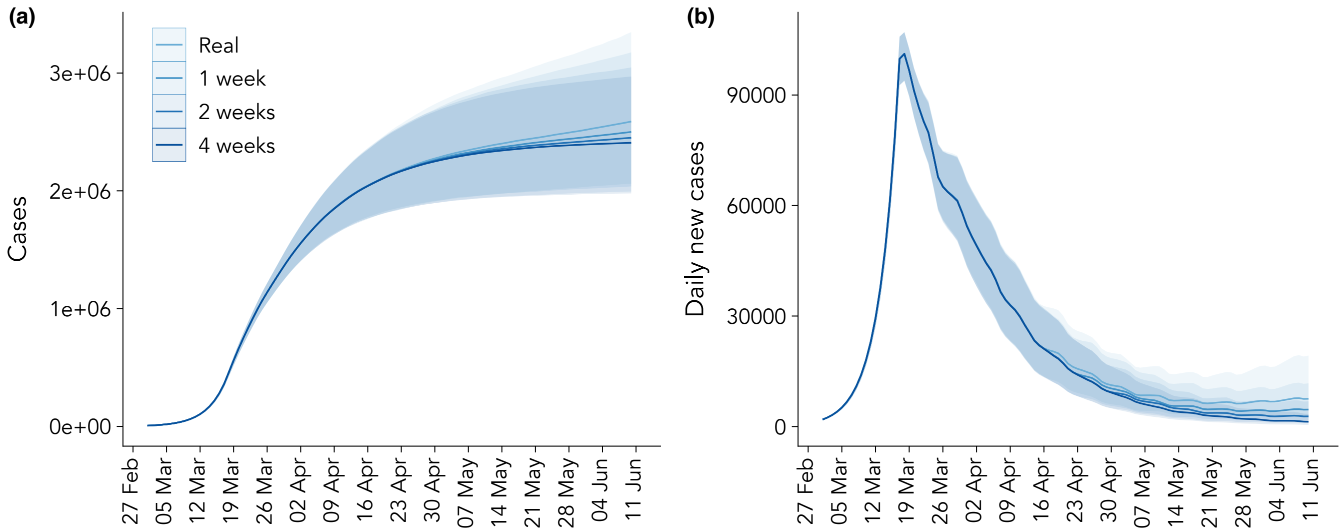

Figure S4. Evolution of the number of number of cases (a), and daily new reported cases (b) as function of time. Lines represent different scenarios where the total lockdown was extended starting on April 10 one week, two weeks, four weeks. For comparison purposes we added the real scenario. Colored ribbons covers a 95% prediction interval.