LEEDS Institute for Data Analytics

The effects of lockdown timing on COVID-19 cases across Europe: A counterfactual modelling study

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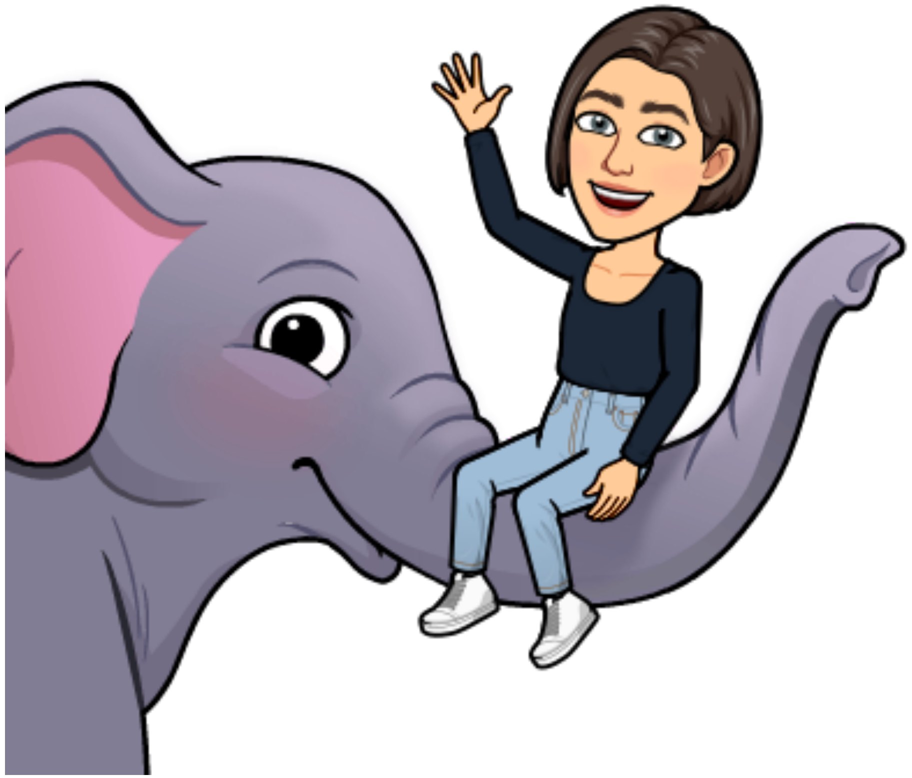
A bit about me

- Postdoctoral research fellow at the University of Leeds
- Research focusses on the integration of formal causal inference methods with simulation-based methods in longitudinal settings



Causal inference

- The formal processes by which we infer cause-and-effect relationships from data
- Sometimes referred to as "*counterfactual prediction*"
- "If I changed *X*, how would *Y* change?"

COVID-19

- Contagious respiratory disease caused by SARS-CoV-2
- First reported in Wuhan, China in December 2019
- Global pandemic declared by WHO on 11 March 2020
- Many features unknown, but clear that virus had high potential for transmission and induced substantial morbidity/mortality

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Coronavirus

This article is more than **1 year old**

New 1,000-bed Wuhan hospital takes its first coronavirus patients

Facility was built in less than two weeks in city at the centre of the viral outbreak

▲ Medical workers in protective suits help transfer the first group of coronavirus patients into the newly completed Huoshenshan temporary field hospital in Wuhan, China. Photograph: Xiao Yijiu/AP

Agence France-Presse

Tue 4 Feb 2020 06.30 GMT

Non-pharmaceutical interventions (NPIs)

- Public health measures that aim to prevent and/or control community transmission of SARS-CoV-2
- Common examples include:
  - Limits on mass gatherings
  - Closing of schools and non-essential shops
  - Restrictions on internal/external movements
  - Orders to stay at home or shelter in place (i.e. ‘lockdown’)

Lockdowns

- Lockdowns generally carry substantial social and economic costs
- Single-country studies (first wave) have generally found that delaying lockdown measures can be even more costly
  - 57% of deaths in the USA could have been avoided by implementing a national lockdown 1 week earlier (Knock et al. 2020)
  - 74% of severe cases in England could have been avoided – and the required length of lockdown halved – had social distancing and lockdown measures been implemented 1 week earlier (Arnold et al. 2022)
- Multi-country studies are much more equivocal

How effective are lockdowns?

Worldwide

- Full lockdown reduced R_0 by 64-85% (Oraby et al. 2021)
- National lockdowns reduced R_t by 0.8-14% (Haug et al. 2020)
- Stay-at-home orders reduced R_t by 13% (Brauner et al. 2021)

Within Europe

- Lockdowns reduced R_t by 81% (Flaxman et al. 2020)
- Stay-at-home orders reduced number of new infections by 4% (Banholzer et al. 2021)

Common methods of analysis

Descriptive or correlational

- Pachetti et al. (2020)
- Plumper and Neumayer (2020)

Regression

- Li et al. (2020)
- Papadoloulos et al. (2020)
- Liu et al. (2021)
- Fuller et al. (2021)

SEIR

- Davies et al. (2020)
- Hyafil and Morina (2020)
- Pei et al. (2020)
- Oraby (2021)

Other

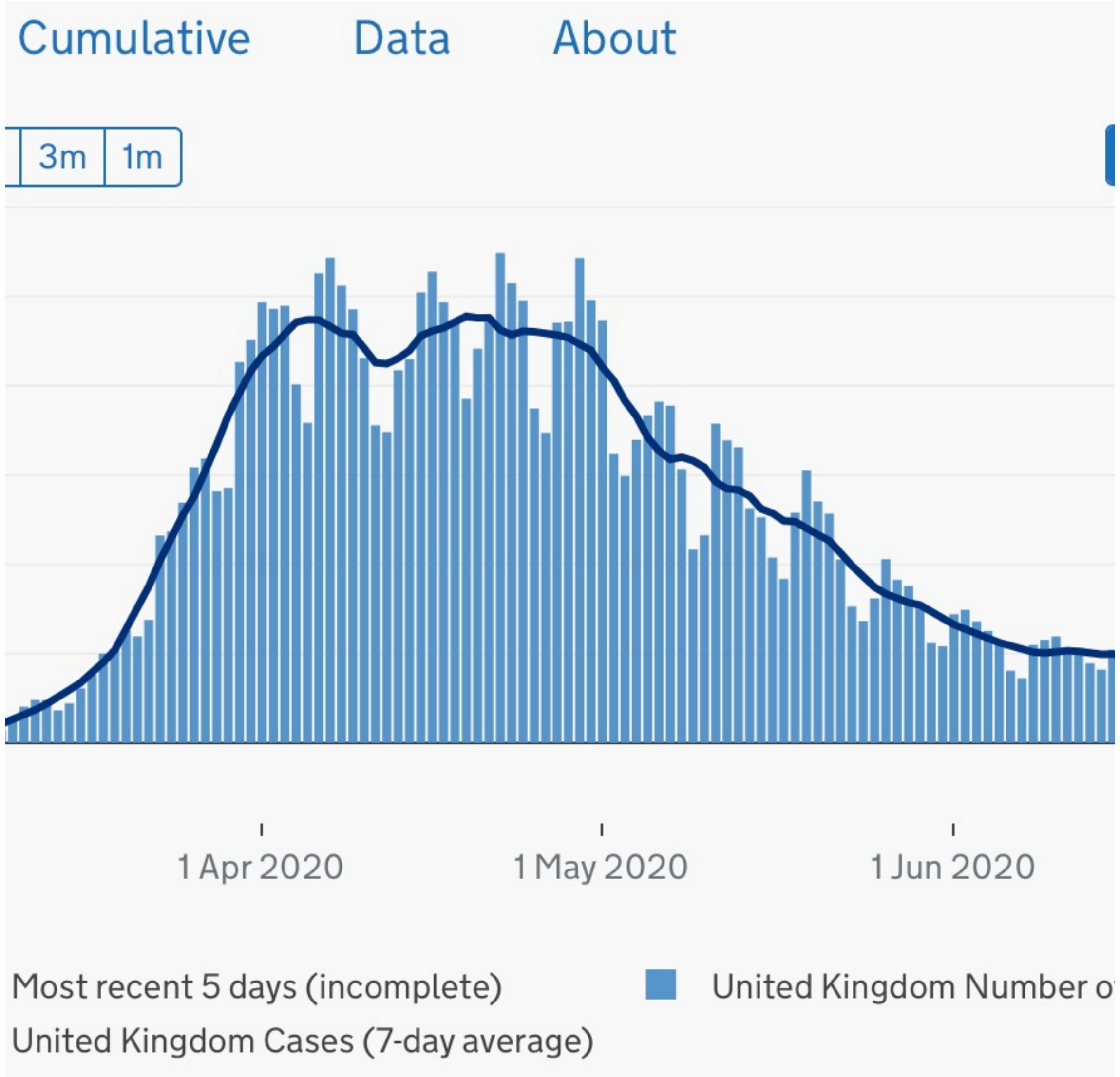
- Baunholzer et al. (2020)
- Flaxman et al. (2020)
- Haug et al. (2020)
- Islam et al. (2020)
- Kontis et al. (2020)
- Brauner et al. (2021)

Methodological challenges

- Between-country heterogeneity makes standard correlational and regression studies impractical to implement and difficult to interpret
  - Demographics
  - Cultural norms
  - Incentivisation systems
  - Testing criteria, procedures, and capacities
- Many methods rely on (and are sensitive to) assumptions about unknown features of the infection and disease processes
  - Transmission rates
  - Basic (R_0) and effective (R_t) reproduction numbers

Methodological challenges (cont.)

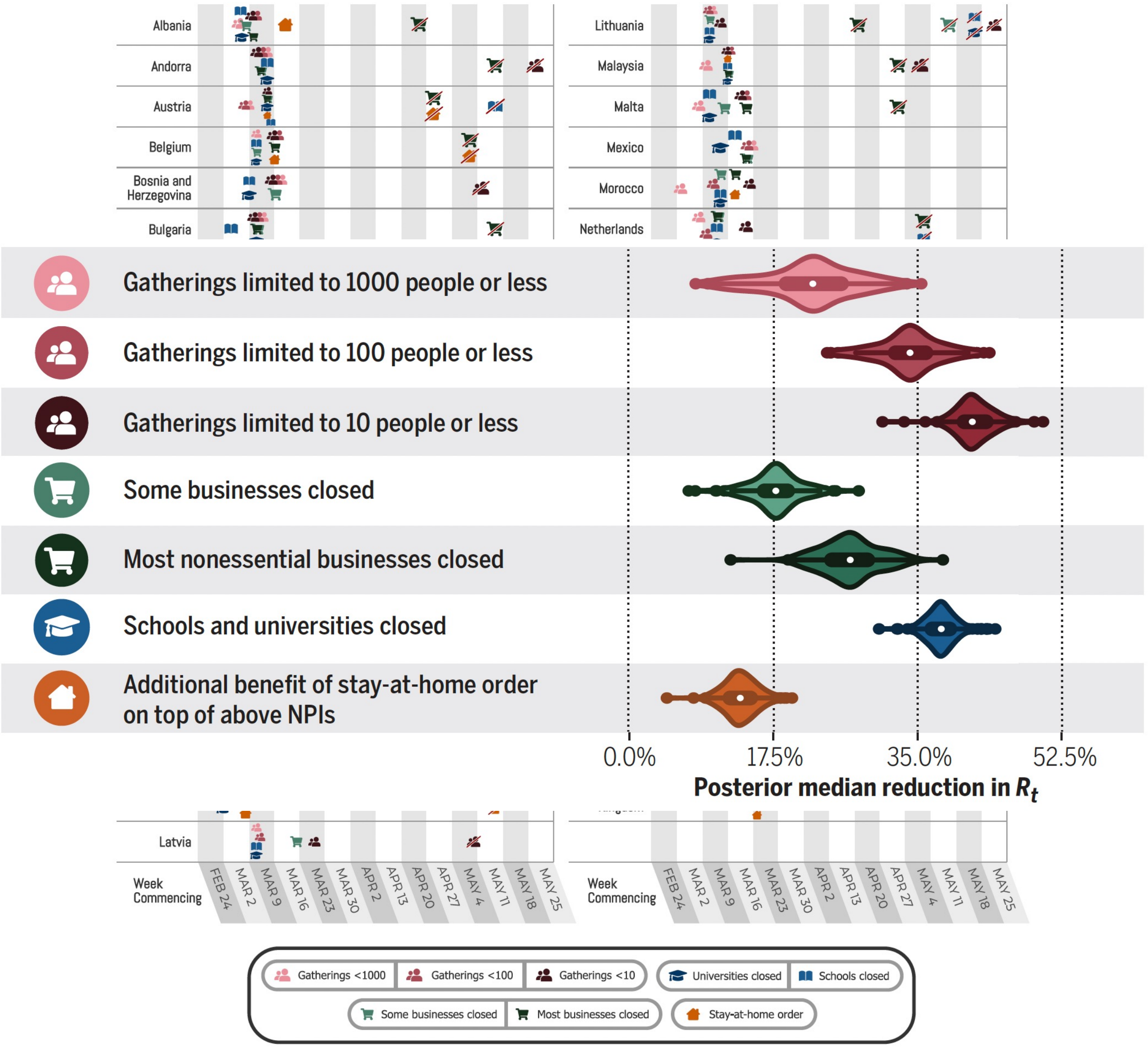
- Observed data are subject to a high degree of autocorrelation and weekday effects
- Intervention effects are observed with an unspecified delay
  - Lag periods vary widely by geography (Liu et al. 2021)
  - Lag periods are generally much longer that incubation period for SARS-CoV-2 (e.g. 2-3 weeks in Canada, Stockdale et al. 2020)



https://coronavirus.data.gov.uk/details/cases
Accessed 20 Sept. 2021

Methodological challenges (cont.)

- High degree of intervention clustering
- Ordering of interventions affects apparent effectiveness
  - Lockdowns are often introduced after a series of less-stringent measures
  - NPIs introduced earliest tend to have greatest effects (Li et al. 2021)



Brauner, J. M., et al. (2021). Inferring the effectiveness of government interventions against COVID-19. *Science, 371*(6531), eabd9338. doi:10.1126/science.abd9338

Solutions

- Model a standardised sequence of interventions:
    1. Initial uncontrolled growth
    2. Growth under initial restrictions
    3. Growth under national lockdown
- Allow for varying lag periods between and within countries
- Accommodate autocorrelation and weekly effects
- Use countries as own comparators
- Bypass need for assumptions about transmission rates
    - Directly model exponential growth

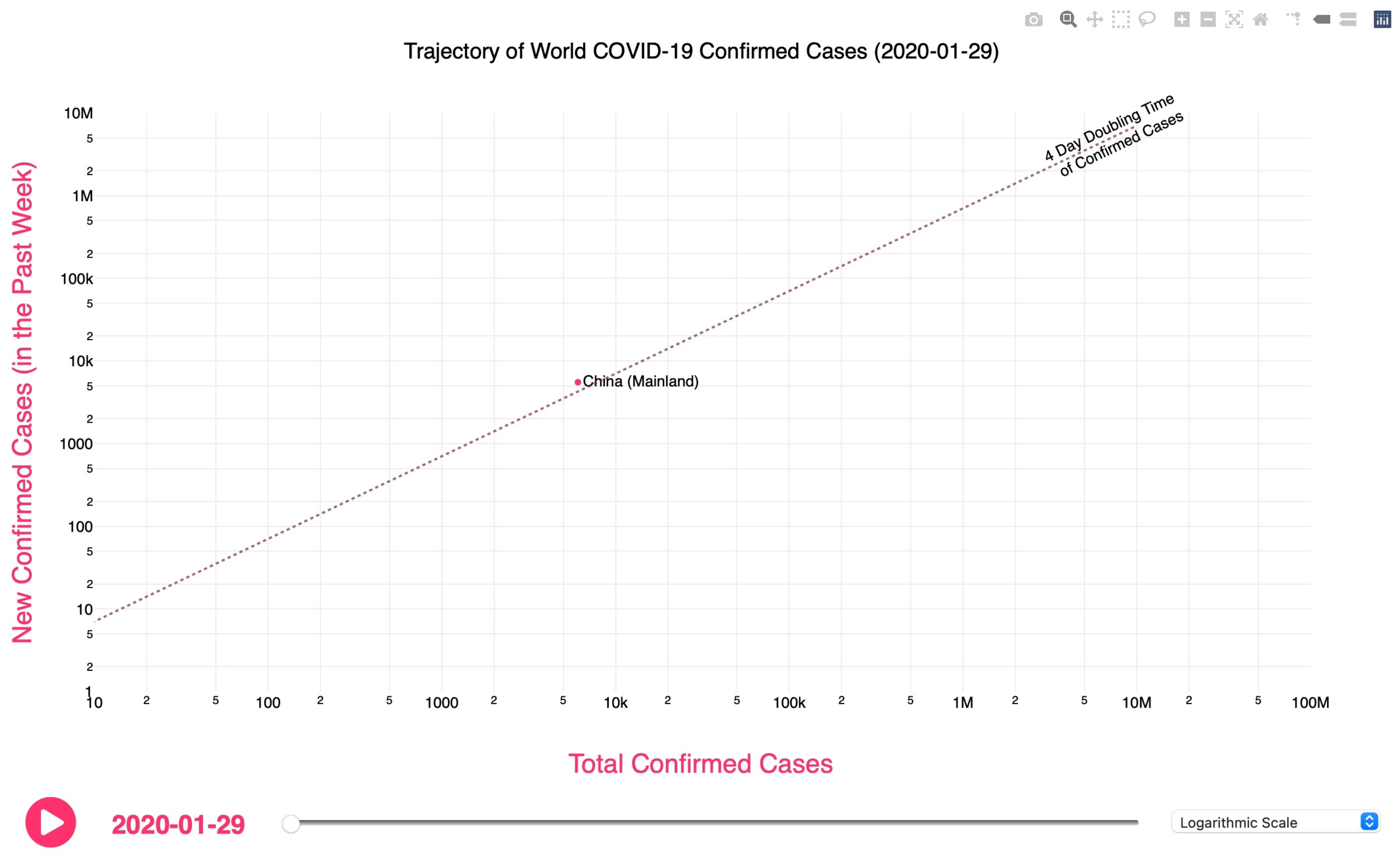
Exponential growth

A causal process whereby the total number of cases on a given day (t) is a multiple (r) of the total number of existing cases:

$$Cumulative\ cases_t = Cumulative\ cases_{t-1} \cdot r$$

$$Incident\ cases_t = Cumulative\ cases_{t-1} \cdot (r-1)$$

This equation implies a linear relationship between cumulative and incident cases over time… *the slope of which should change due to social distancing and lockdown measures*



Created by Aatish Bhatia in collaboration with Minute Physics · World data provided by Johns Hopkins University (updated daily around 00:00 UTC / 20:00 ET) · US state data provided by NYTimes (updated daily around 16:00 UTC / 12:00 ET)· Shortcuts: +/- for daily changes, space to play/pause · Credits & Source · Stay safe!

https://aatishb.com/covidtrends

Research question

To what extent does delaying implementation of initial (often voluntary) measures and more severe lockdown measures increase total case numbers and ultimately prolong the length of lockdown required?

Study sample & data sources

Study sample

- First wave of COVID-19
- 44 European countries eligible for inclusion

Data sources

- COVID-19 Data Repository by the Center for Systems Science and Engineering at Johns Hopkins University
- Oxford COVID-19 Government Response Tracker
- World Bank

Analysis overview

01

Identify important dates

02

Estimate growth parameters

03

Simulate counterfactual scenarios

01 Identification of important dates

Date of first restriction:

- First date where any of the specified containment and closure policies were recommended or required

Lockdown:

- First date for which either a stay-at-home order or 3+ other containment and closure policies were required nationally

Date of lockdown easing *(i.e. end of full lockdown)*:

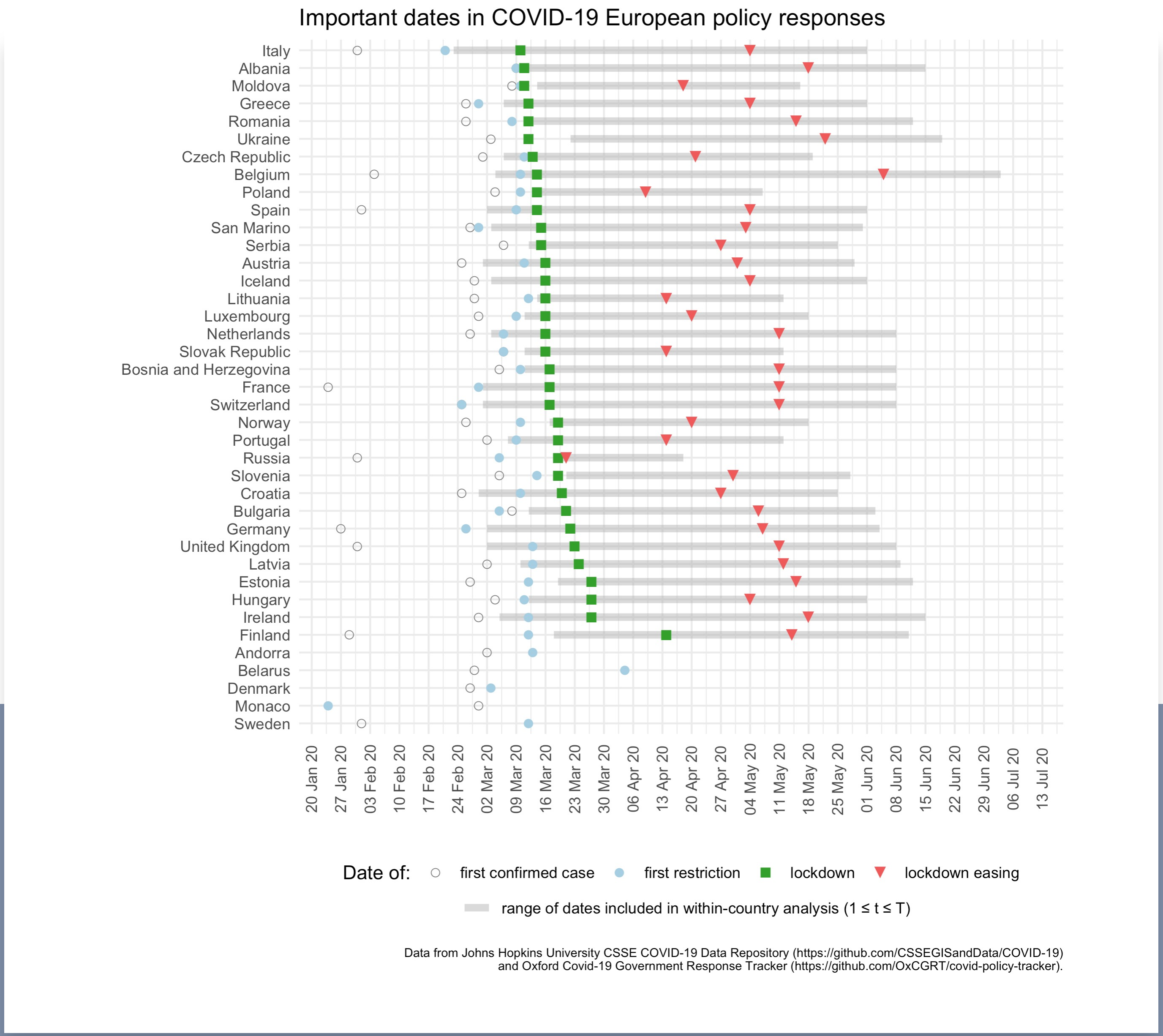
- First date subsequently for which the total number of measures required nationally decreased

End of first wave:

- 28 days after the date of lockdown easing

39 European countries had both cases and policy data available

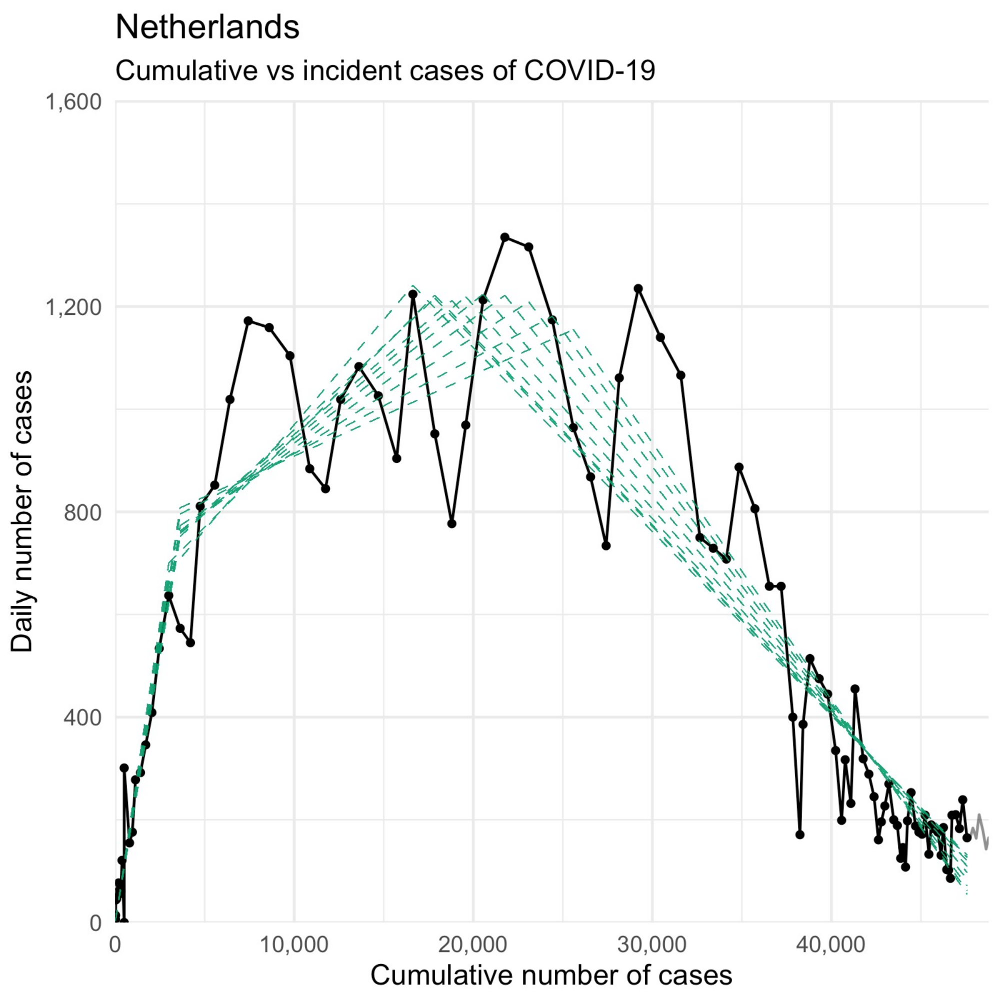
33 entered lockdown & had estimable growth parameters

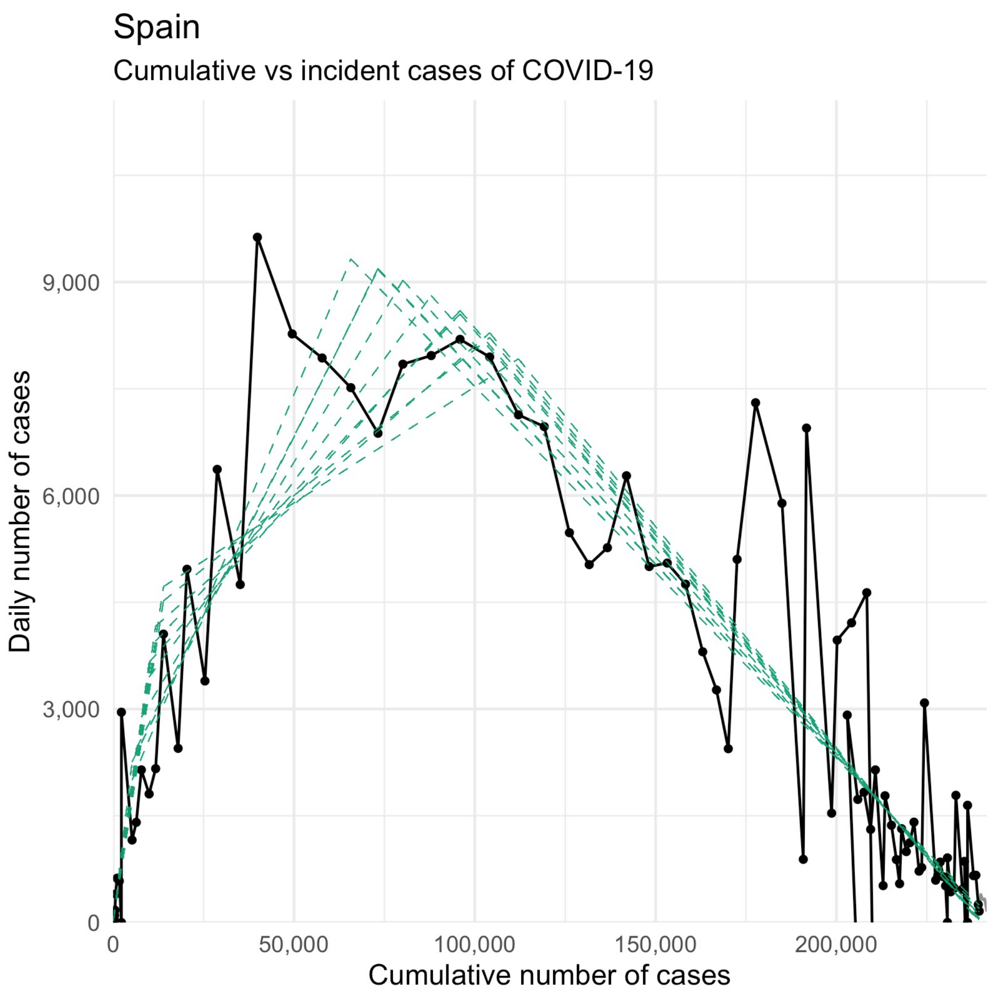


02 Parameter estimation

- We considered 3 potential periods of growth:
    1. Initial uncontrolled growth
    2. Growth under initial restrictions
    3. Growth under national lockdown

- Using Arima spline models, we estimated for each country:
    - The 10 most likely dates for which each period of growth began (i.e. the knot dates)
        - Relative likelihood of each pair
    - The growth factor r (and standard deviation SD_r) governing each period of growth


Netherlands
Cumulative vs incident cases of COVID-19
1,600
1,200
800
400
0
0
10,000
20,000
30,000
40,000
Daily number of cases
Cumulative number of cases


Spain
Cumulative vs incident cases of COVID-19
9,000
6,000
3,000
0
0
50,000
100,000
150,000
200,000
Daily number of cases
Cumulative number of cases

Key findings from parameter estimation

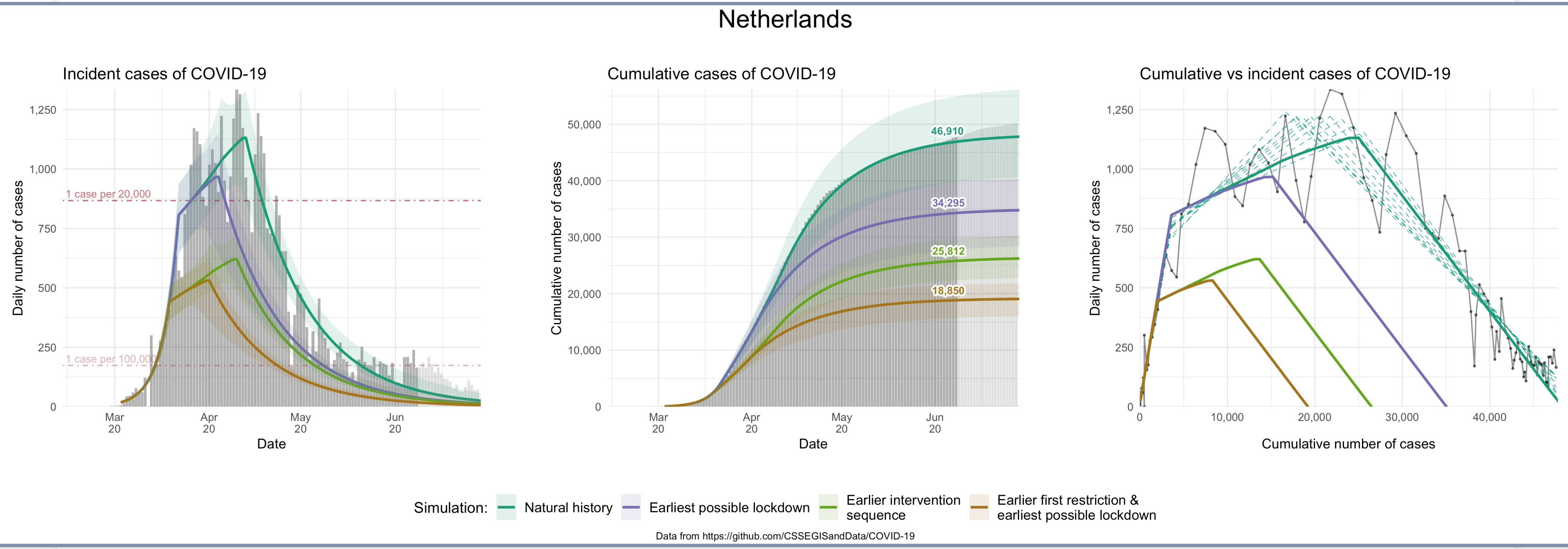
- Weighted median lag periods across all countries:
  - 14.0 (Q1-Q3: 10.7-18.0) days from the first restriction to the first knot date
  - 20.2 (Q1-Q3: 16.0-24.0) days from lockdown to the second knot date
- Weighted median growth factors across all countries:
  - 1.222 (Q1-Q3: 1.156-1.296) during initial uncontrolled growth
  - 1.048 (Q1-Q3: 1.015-1.060) during growth under initial restrictions
  - 0.957 (Q1-Q3: 0.944-0.971) during growth under lockdown

03 Counterfactual simulations

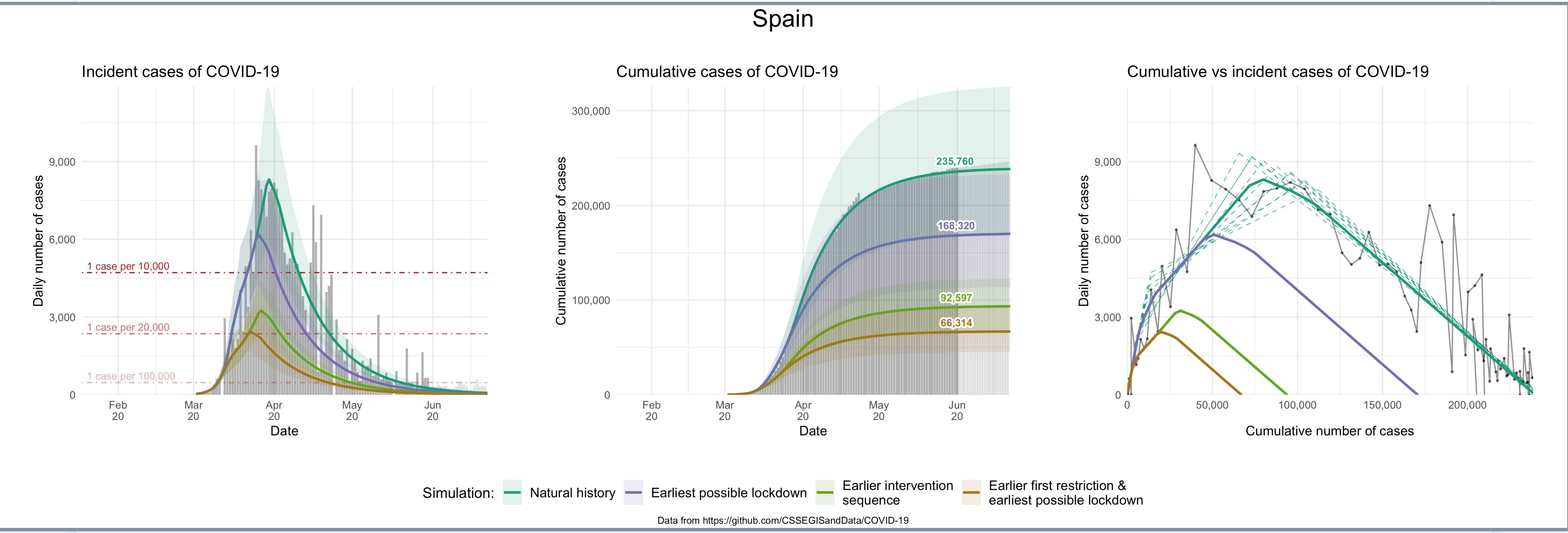
- We used stochastic simulations to estimate the growth of COVID-19 cases within each country during the first wave under 4 scenarios:
  1. Natural growth
  2. Earliest possible lockdown
  3. Earlier intervention sequence (3 days)
  4. Earlier first restriction (3 days) and earliest possible lockdown
- Under each scenario, we estimated:
  - The total number of first wave cases
  - The required length of full lockdown *(i.e. the number of days to reach the same daily case threshold that was observed when lockdown was actually eased)*

Some simulation details

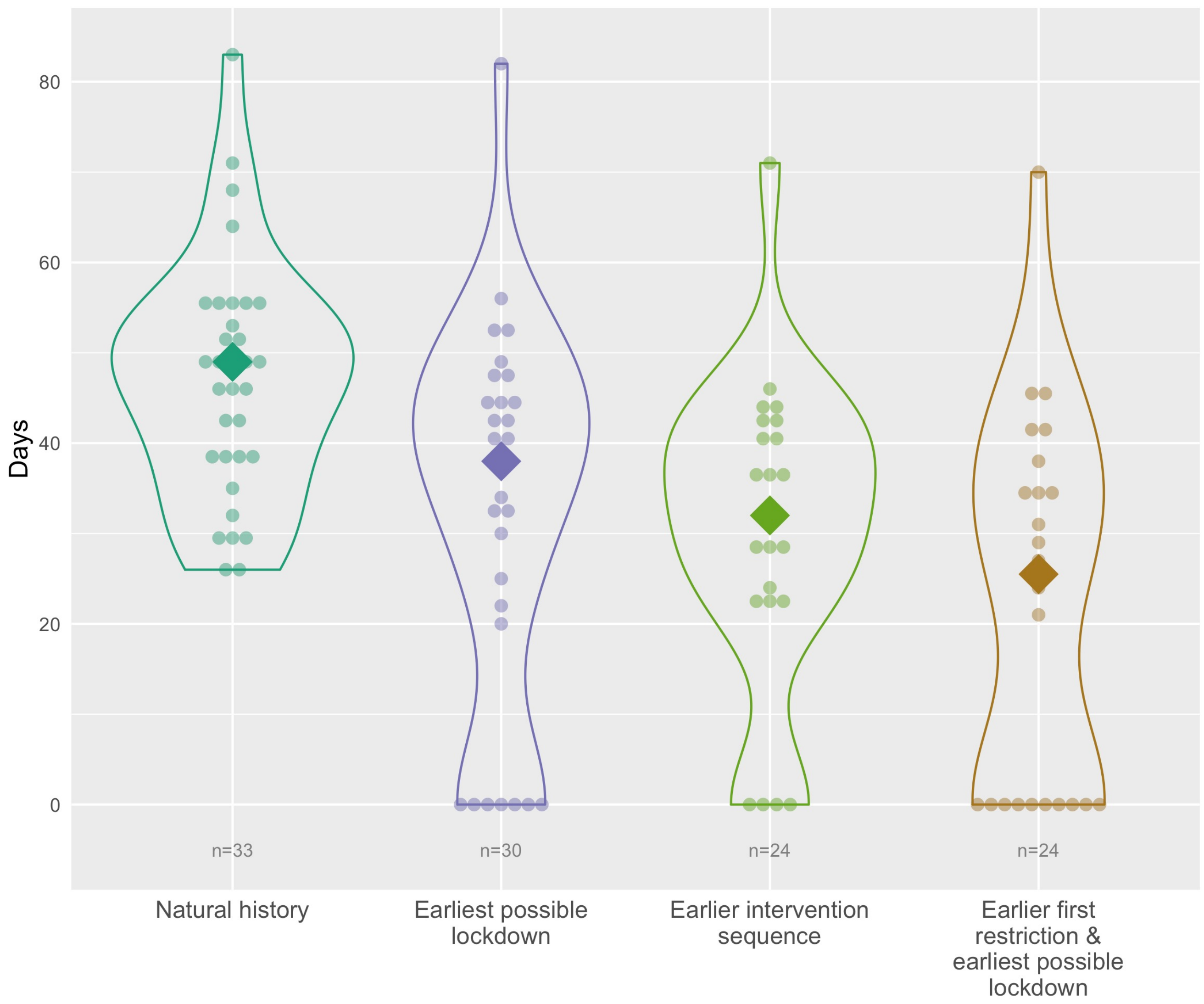
- All scenarios were simulated 100,000 times
  - Median and 95% simulation interval calculated
- A random growth factor was drawn from a lognormal distribution for each day in each simulation, according to the period of growth in which it fell
- All knot date pairs identified as most likely were used, with their frequency corresponding to their relative likelihood
- ***Note:*** *not all counterfactuals could be computed for all countries*
  - The first knot date could not occur (counterfactually) before the simulation period began



Netherlands
Incident cases of COVID-19
Cumulative cases of COVID-19
Cumulative vs incident cases of COVID-19
Daily number of cases
Cumulative number of cases
Date
1 case per 20,000
1 case per 100,000
46,910
34,295
25,812
18,850
Mar 20
Apr 20
May 20
Jun 20
Simulation:
Natural history
Earliest possible lockdown
Earlier intervention sequence
Earlier first restriction & earliest possible lockdown
Data from https://github.com/CSSEGISandData/COVID-19


Spain
Incident cases of COVID-19
Daily number of cases
9,000
6,000
3,000
0
1 case per 10,000
1 case per 20,000
1 case per 100,000
Feb 20
Mar 20
Apr 20
May 20
Jun 20
Date
Cumulative cases of COVID-19
Cumulative number of cases
300,000
200,000
100,000
0
235,760
168,320
92,597
66,314
Cumulative vs incident cases of COVID-19
50,000
100,000
150,000
200,000
Cumulative number of cases
Simulation:
Natural history
Earliest possible lockdown
Earlier intervention sequence
Earlier first restriction & earliest possible lockdown
Data from https://github.com/CSSEGISandData/COVID-19

Length of full lockdown required in all simulations



Simulation	Total cases in first wave: Median percentage change* (Q1, Q3)	N	Length of full lockdown: Median percentage change* (Q1, Q3)	N
Earliest possible lockdown	-28.61 (-51.18, -7.22)	33	-18.63 (-57.73, 0.00)	30
Earlier intervention sequence	-44.98 (-54.41, -34.08)	25	-28.84 (-43.04, -19.48)	24
Earlier first restriction and earliest possible lockdown	-60.15 (-71.87, -49.10)	25	-36.92 (-100.00, -19.35)	24

compared to natural history

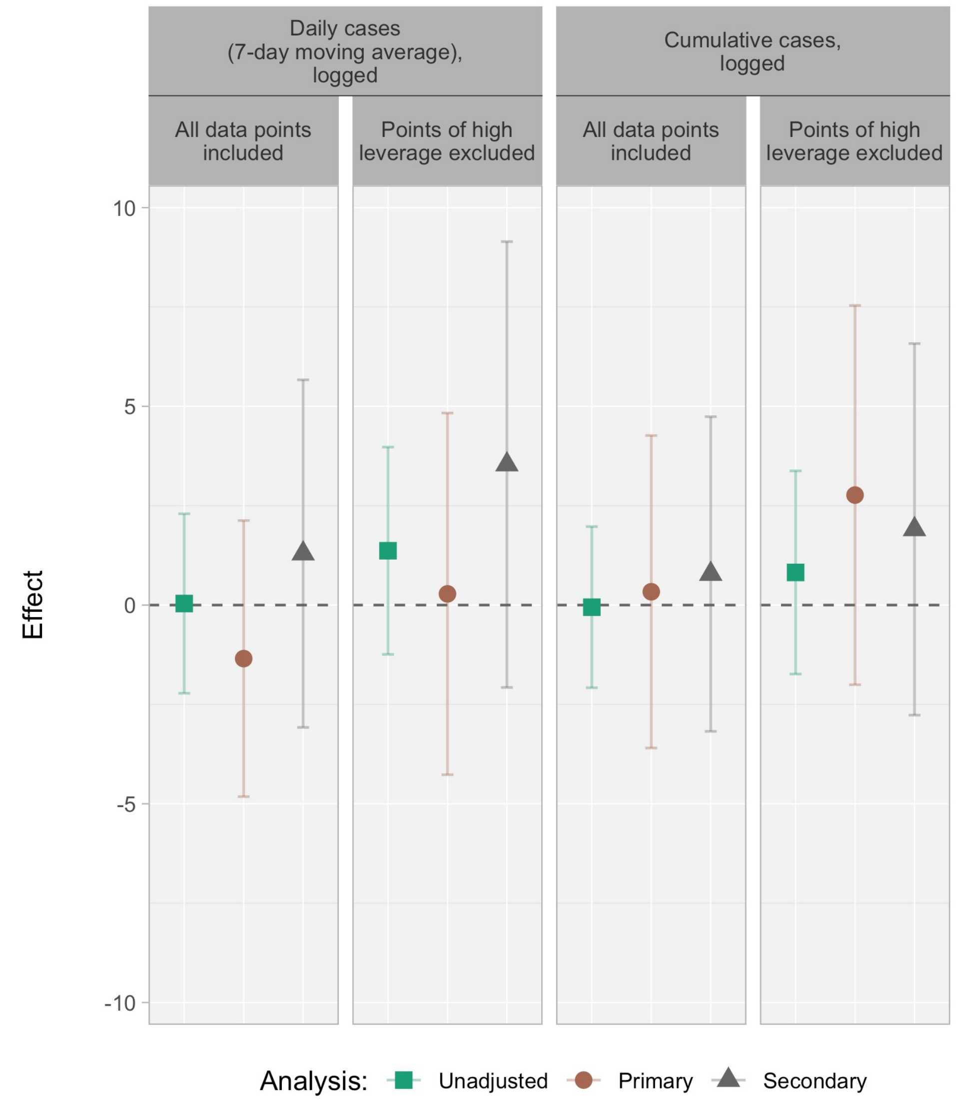
Other important findings

- Significant between-county heterogeneity wrt key parameters
  - Outbreak scales
  - Growth factors
  - Lag periods

Comparison with regression analysis

- Exposure: number of cases on the date of lockdown (logged)
    1. Daily (7-day moving average)
    2. Cumulative
- Outcome: length of full lockdown
- Covariates:
    - Area size, GDP, total population (primary analysis)
    - Area size, GDP, population (0-14, 15-64, 65+), urban population, total healthcare expenditure (secondary analysis)

- No clear or substantial relationship between lockdown timing and length of full lockdown
- Primary effect estimates ranged from -1.35 (95% CI: -4.82 to 2.13) to 0.33 (95% CI: -3.60 to 4.27)
    - 1 *fewer* day of lockdown for every 210% increase in daily cases to 1 *more* day of lockdown for every 2070% increase in total cases on the date of lockdown



Strengths

- Simulations accounted for between-country heterogeneity by evaluating the counterfactuals within each country separately
- No assumptions about transmission rates or reproduction numbers were required
  - Parameters of interest could be directly estimated from observed data
- Accommodated variation and uncertainty wrt lag periods and growth factors
- Accommodated autocorrelation and weekly effects

Limitations

- Modelling provides only an incomplete summary of the first wave
  - Confirmed cases < true infections
- Analyses did not account for variation in lockdown stringency between countries or increasing stringency of restrictions within different periods of growth
- Other assumptions required:
  - Testing levels remained relatively constant across the first wave
  - Changes in the growth factor were the direct result of NPIs
  - Interventions produced a sharp change in the growth factor

Conclusions & implications

- It is important to act both strongly and swiftly to minimize the spread of COVID-19 when case numbers are increasing exponentially
- There exists substantial between-country heterogeneity that must be adequately taken into account when conducting multi-country studies
- A counterfactual framework is useful for conceptualizing and evaluating the effects of various non-pharmaceutical interventions

References (1)

1. Arnold, K. et al. (2022). Estimating the effects of lockdown timing on COVID-19 cases and deaths in England: A counterfactual modelling study. *PLoS ONE (in press).*
2. Banholzer, N., et al. (2021). Estimating the effects of non-pharmaceutical interventions on the number of new infections with COVID-19 during the first epidemic wave. *PLoS ONE, 16*(6), e0252827. doi:10.1371/journal.pone.0252827
3. Brauner, et al. (2021). Inferring the effectiveness of government interventions against COVID-19. *Science, 371*(6531), eabd9338. doi:10.1126/science.abd9338
4. Davies, N. G., et al. (2020). Effects of non-pharmaceutical interventions on COVID-19 cases, deaths, and demand for hospital services in the UK: a modelling study. *The Lancet Public Health, 5*(7), e375-e385. doi:10.1016/S2468-2667(20)30133-X
5. Dong E., et al. (2020). An interactive web-based dashboard to track COVID-19 in real time. *The Lancet Infectious Diseases,* **20**(5), 533-4.
6. Flaxman, S., et al. (2020). Estimating the effects of non-pharmaceutical interventions on COVID-19 in Europe. *Nature, 584*(7820), 257-261. doi:10.1038/s41586-020-2405-7
7. Fuller, J. A., Hakim, A., Victory, K. R., Date, K., Lynch, M., Dahl, B., & Henao, O. (2021). *Mitigation Policies and COVID-19–Associated Mortality — 37 European Countries, January 23–June 30, 2020*.
8. Haug, N., et al. (2020). Ranking the effectiveness of worldwide COVID-19 government interventions. *Nature Human Behaviour, 4*(12), 1303-1312. doi:10.1038/s41562-020-01009-0
9. Hale T., et al. (2020). Oxford COVID-19 Government Response Tracker. Blavatnik School of Government.
10. Hyafil, A., & Moriña, D. Analysis of the impact of lockdown on the reproduction number of the SARS-Cov-2 in Spain. *Gaceta Sanitaria*. doi:10.1016/j.gaceta.2020.05.003
11. Islam, N., et al. (2020). Physical distancing interventions and incidence of coronavirus disease 2019: natural experiment in 149 countries. *BMJ, 370*, m2743. doi:10.1136/bmj.m2743

References (2)

12. Knock, E. S., et al. (2020). *Report 41 - The 2020 SARS-CoV-2 epidemic in England: key epidemiological drivers and impact of interventions*. Retrieved from https://www.imperial.ac.uk/mrc-global-infectious-disease-analysis/covid-19/report-41-rtm/
13. Kontis, V., et al. (2020). Magnitude, demographics and dynamics of the effect of the first wave of the COVID-19 pandemic on all-cause mortality in 21 industrialized countries. *Nature Medicine, 26*(12), 1919-1928. doi:10.1038/s41591-020-1112-0
14. Li, Y., et al. (2021). The temporal association of introducing and lifting non-pharmaceutical interventions with the time-varying reproduction number (R) of SARS-CoV-2: a modelling study across 131 countries. *The Lancet Infectious Diseases, 21*(2), 193-202. doi:10.1016/S1473-3099(20)30785-4
15. Liu, Y., et al. (2021). The impact of non-pharmaceutical interventions on SARS-CoV-2 transmission across 130 countries and territories. *BMC Medicine, 19*(1), 40. doi:10.1186/s12916-020-01872-8
16. Oraby, T., et al. (2021). Modeling the effect of lockdown timing as a COVID-19 control measure in countries with differing social contacts. *Scientific Reports, 11*(1), 3354. doi:10.1038/s41598-021-82873-2
17. Pachetti, M., et al. (2020). Impact of lockdown on Covid-19 case fatality rate and viral mutations spread in 7 countries in Europe and North America. *Journal of Translational Medicine, 18*(1), 338. doi:10.1186/s12967-020-02501-x
18. Papadopoulos, D. I., et al. (2020). The impact of lockdown measures on COVID-19: a worldwide comparison. *medRxiv*, 2020.2005.2022.20106476. doi:10.1101/2020.05.22.20106476
19. Pei, S., Kandula, S., & Shaman, J. (2020). Differential effects of intervention timing on COVID-19 spread in the United States. *Science Advances, 6*(49), eabd6370. doi:10.1126/sciadv.abd6370
20. Plümper, T., & Neumayer, E. (2020). Lockdown policies and the dynamics of the first wave of the Sars-CoV-2 pandemic in Europe. *Journal of European Public Policy*, 1-21. doi:10.1080/13501763.2020.1847170
21. Stockdale, et al. (2020). Long time frames to detect the impact of changing COVID-19 control measures. *medRxiv*. doi:10.1101/2020.06.14.20131177
22. The World Bank Group. (2021). World Bank Open Data: Free and open access to global development data. https://data.worldbank.org.

Interactive dashboard

Link

Many thanks to Dr Camila Rangel-Smith and Dr James Robinson (both of The Alan Turing Institute) for creating the dashboard