

Predictive Modeling

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FOR DEMOGRAPHIC RESEARCH

Parameter-centric modeling

TABELLE 5: COX REGRESSION MIT INTERAKTIONSEFFEKT (QUELLE: ESA 2009, EIGENE BERECHNUNG UND DARSTELLUNG)

Characteristic	HR ¹	95% CI ¹	p-value
sex			
Female	—	—	
Male	2.49	2.02, 3.07	<0.001
cohort			
_1945_1949	—	—	
_1950_1959	1.75	1.44, 2.12	<0.001
_1960_1969	1.71	1.41, 2.08	<0.001
_1970_1979	1.67	1.38, 2.03	<0.001
_1980_1991	1.71	1.42, 2.05	<0.001
bildung			
hoher_Schulabschluss	—	—	
mittlerer_Schulabschluss	1.39	1.29, 1.49	<0.001
niedriger_Schulabschluss	1.49	1.36, 1.62	<0.001
Schüler_in	0.90	0.75, 1.09	0.3
sex * cohort			
Male * _1950_1959	0.60	0.46, 0.77	<0.001
Male * _1960_1969	0.57	0.44, 0.74	<0.001
Male * _1970_1979	0.52	0.40, 0.67	<0.001
Male * _1980_1991	0.47	0.37, 0.59	<0.001

¹HR = Hazard Ratio, CI = Confidence Interval

Balling (2022). Das Rauchverhalten von Männern und Frauen in verschiedenen Kohorten.

Parameter-centric modeling vs. predictive modeling

Balling (2022). Das Rauchverhalten von Männern und Frauen in verschiedenen Kohorten.

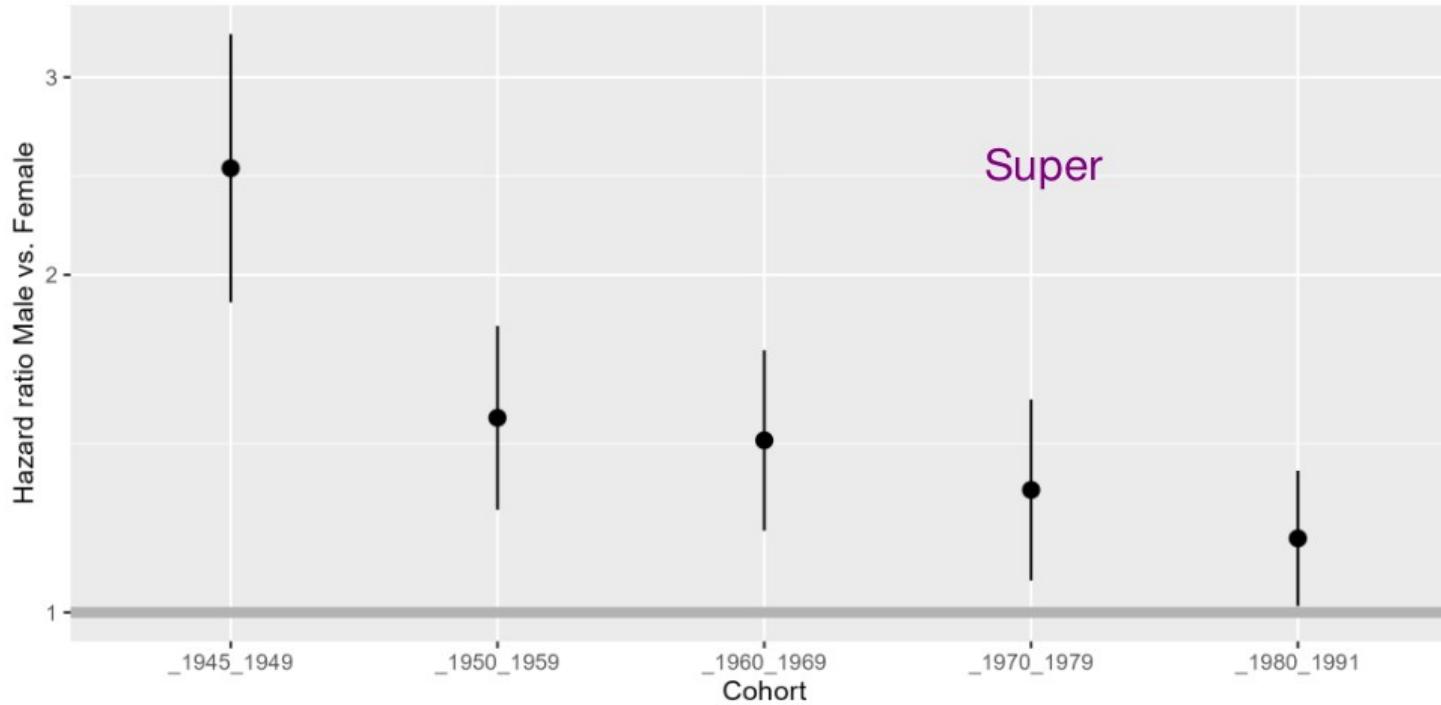
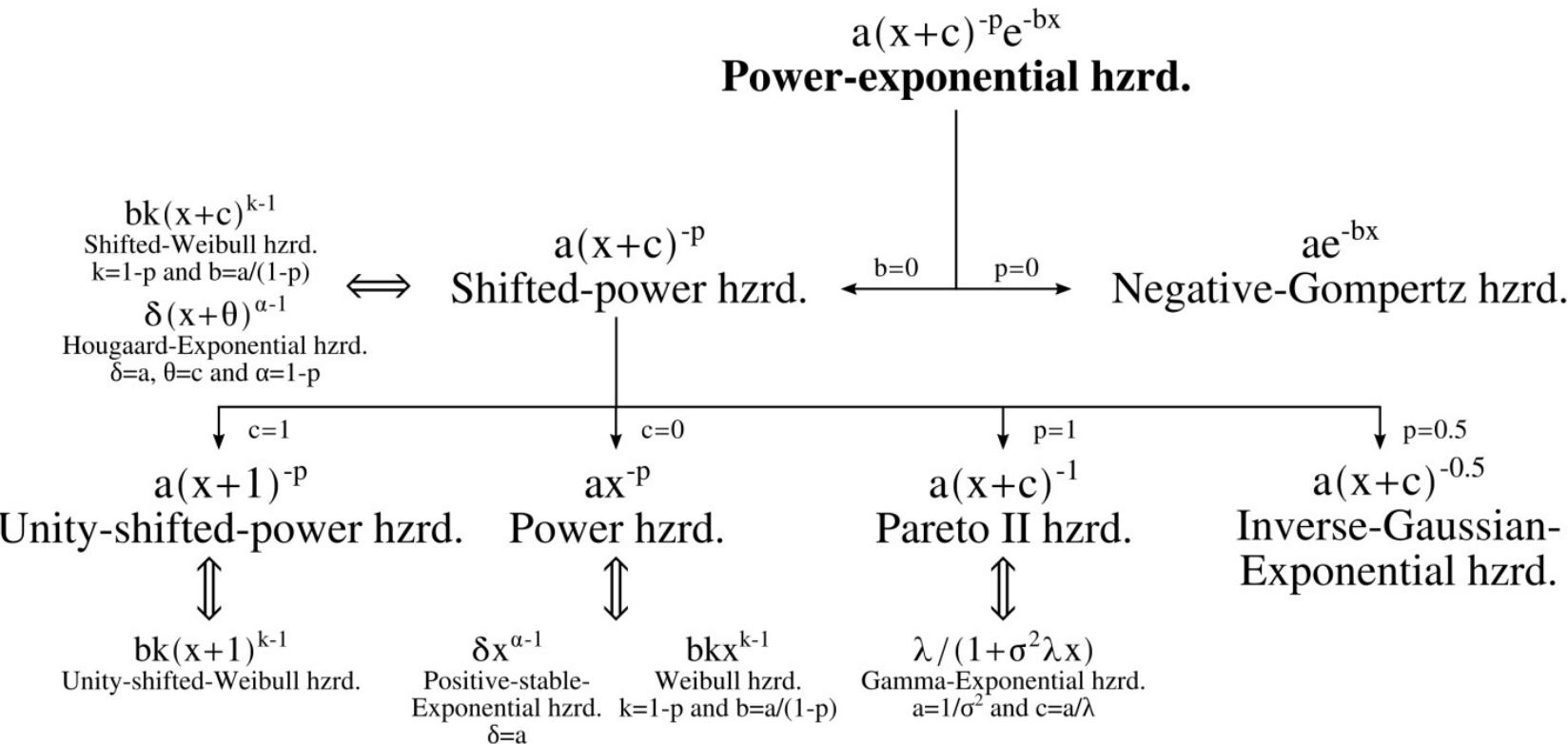


ABBILDUNG 6: INTERAKTIONSEFFEKT (QUELLE: ESA 2009, EIGENE BERECHNUNG UND DARSTELLUNG)

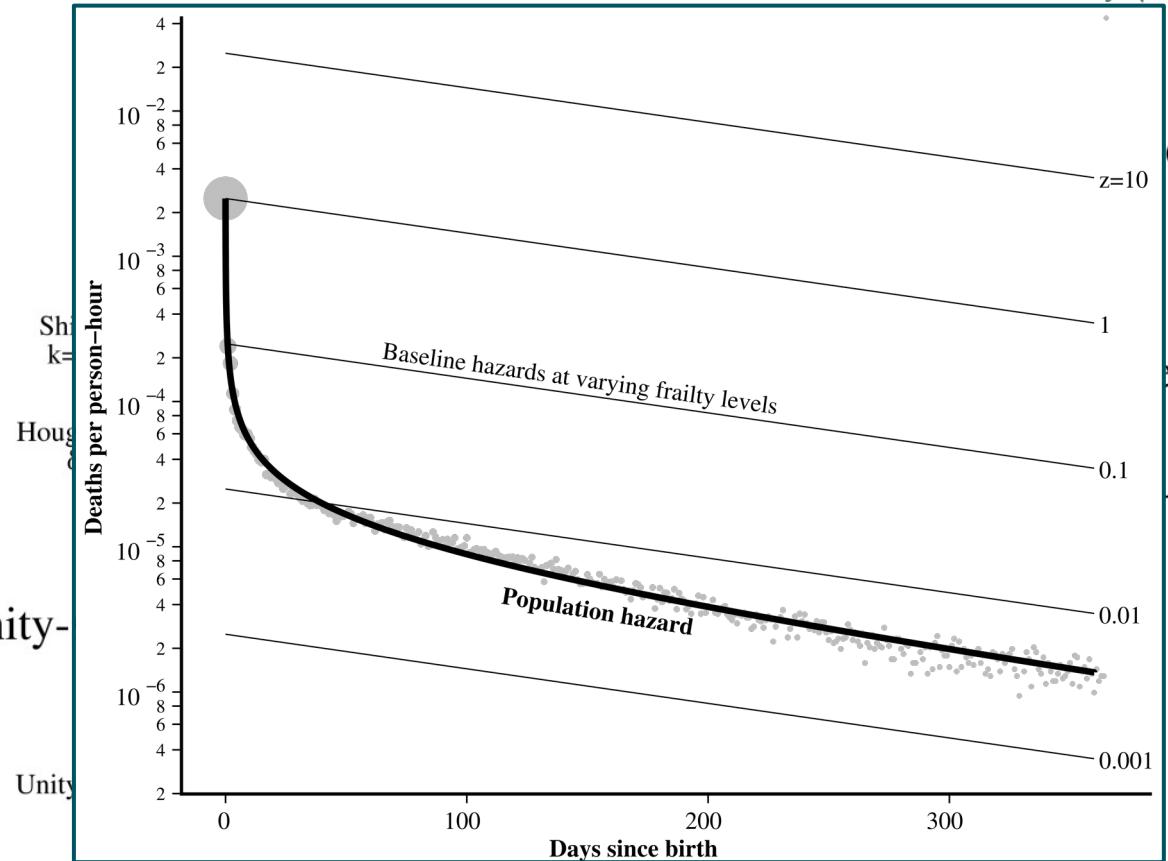
Parameter-centric modeling vs. predictive modeling

Schöley (2020). The dynamics of ontogenescence. [Github link](#).



Parameter-centric modeling vs. predictive modeling

Schöley (2020). The dynamics of ontogenescence. [Github link](#).



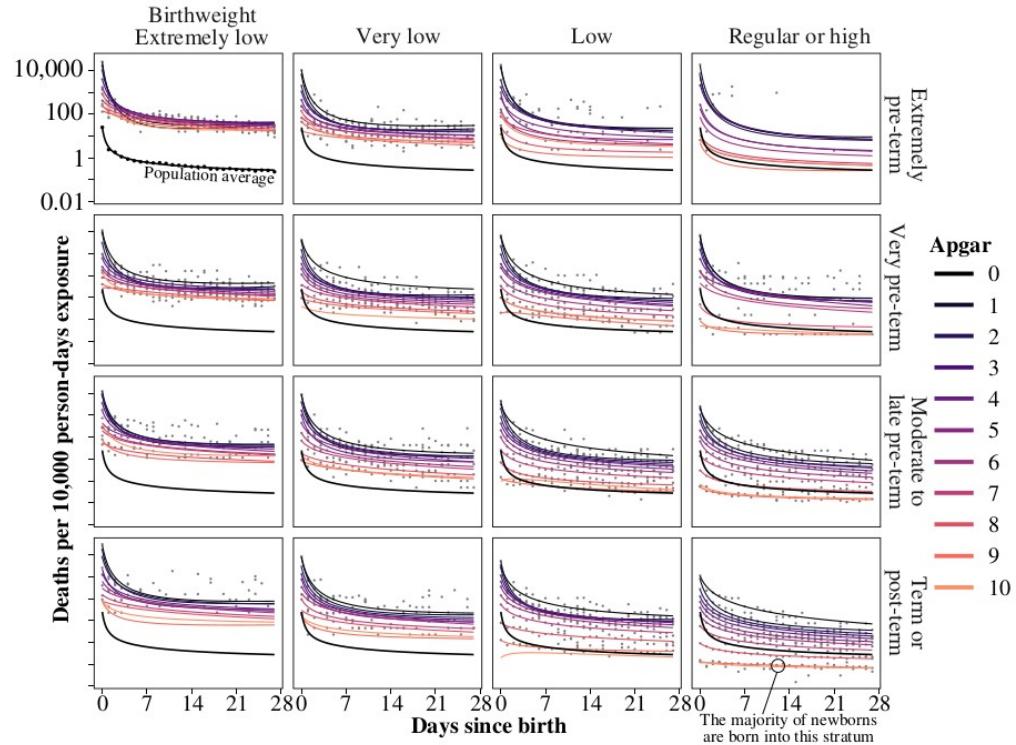
d.

ae^{-bx}
negative-Gompertz hzrd.

$p=0.5$
 $a(x+c)^{-0.5}$
Inverse-Gaussian-
Exponential hzrd.

Parameter-centric modeling vs. predictive modeling

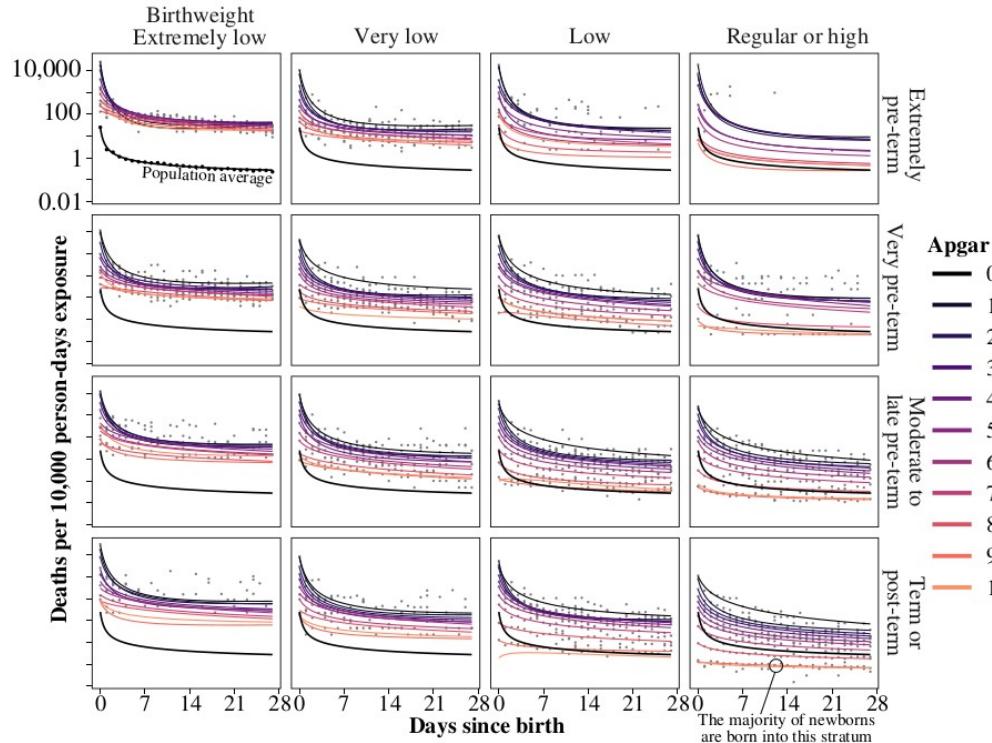
Figure 3: Estimated hazard rates versus life table mortality rates over age by prematurity, birth weight, and Apgar score. There is substantial heterogeneity in the level and the shape of the neonatal hazard trajectories ruling out the hypothesis of proportional frailties. The black line in each panel shows the estimated hazard trajectory for the entire birth cohort.



Schöley (2020). The dynamics of ontogenescence. [Github link](#).

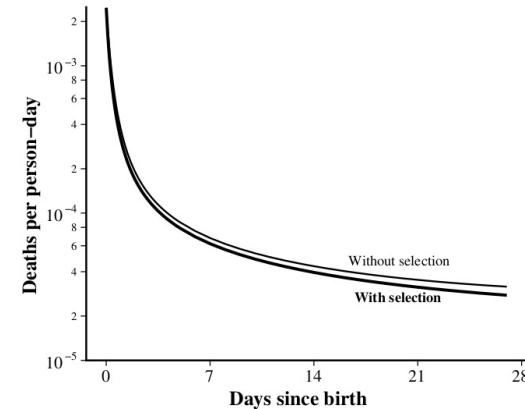
Parameter-centric modeling vs. predictive modeling

Figure 3: Estimated hazard rates versus life table mortality rates over age by prematurity, birth weight, and Apgar score. There is substantial heterogeneity in the level and the shape of the neonatal hazard trajectories ruling out the hypothesis of proportional frailties. The black line in each panel shows the estimated hazard trajectory for the entire birth cohort.



Schöley (2020). The dynamics of ontogenescence. [Github link](#).

Figure 4: Keeping the population composition fixed at the distribution observed at birth only results in a minor change of the population hazard trajectory.



Predictive modeling in demography: Indirect estimation



Aleksei Raksha

Rogue Demographer Says Russia May Top Europe in Covid Deaths

- Former statistics agency employee has criticized virus data
- Daily death numbers need to be tripled, demographer says



LIVE ON BLO
Watch Live T
Listen to Live

Photographer: Dimitar Dilkoff/AFP via Getty Images

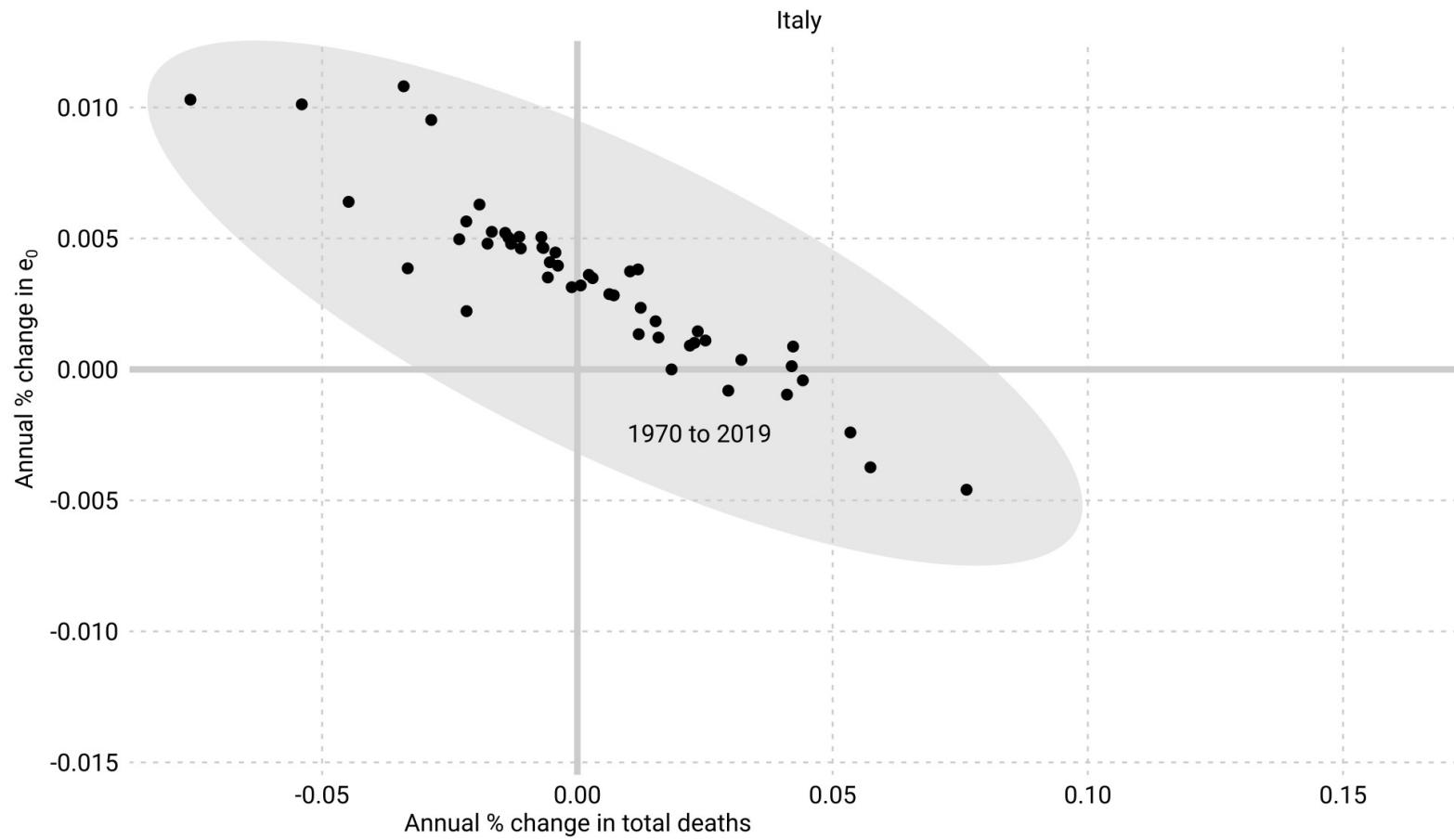
By Anya Andrianova and Stepan Kravchenko

October 20, 2020 at 6:00 AM GMT+2 Updated on October 20, 2020

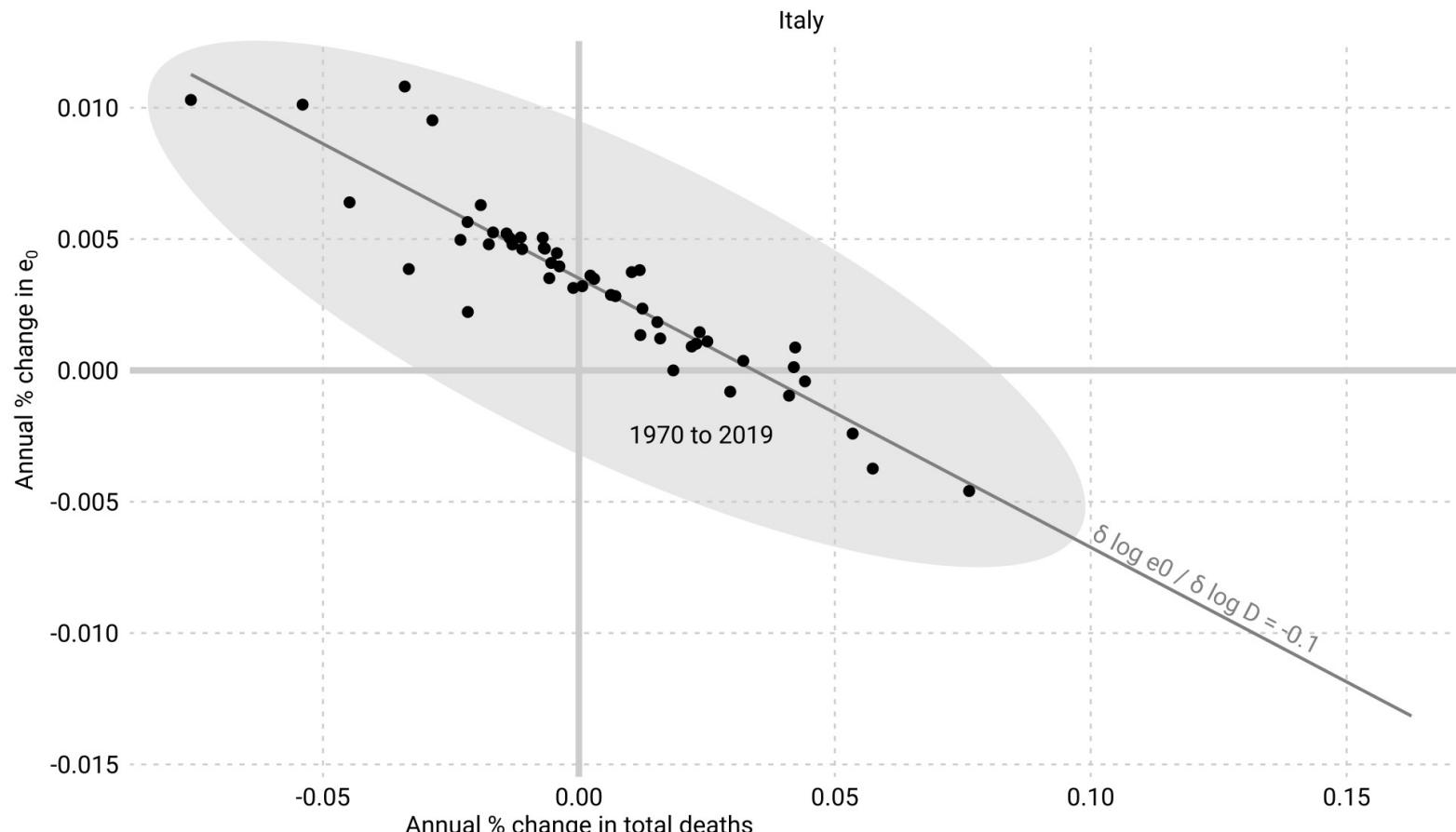
at 12:36 PM GMT+2

Bloomberg. October 20, 2020. [Link](#).

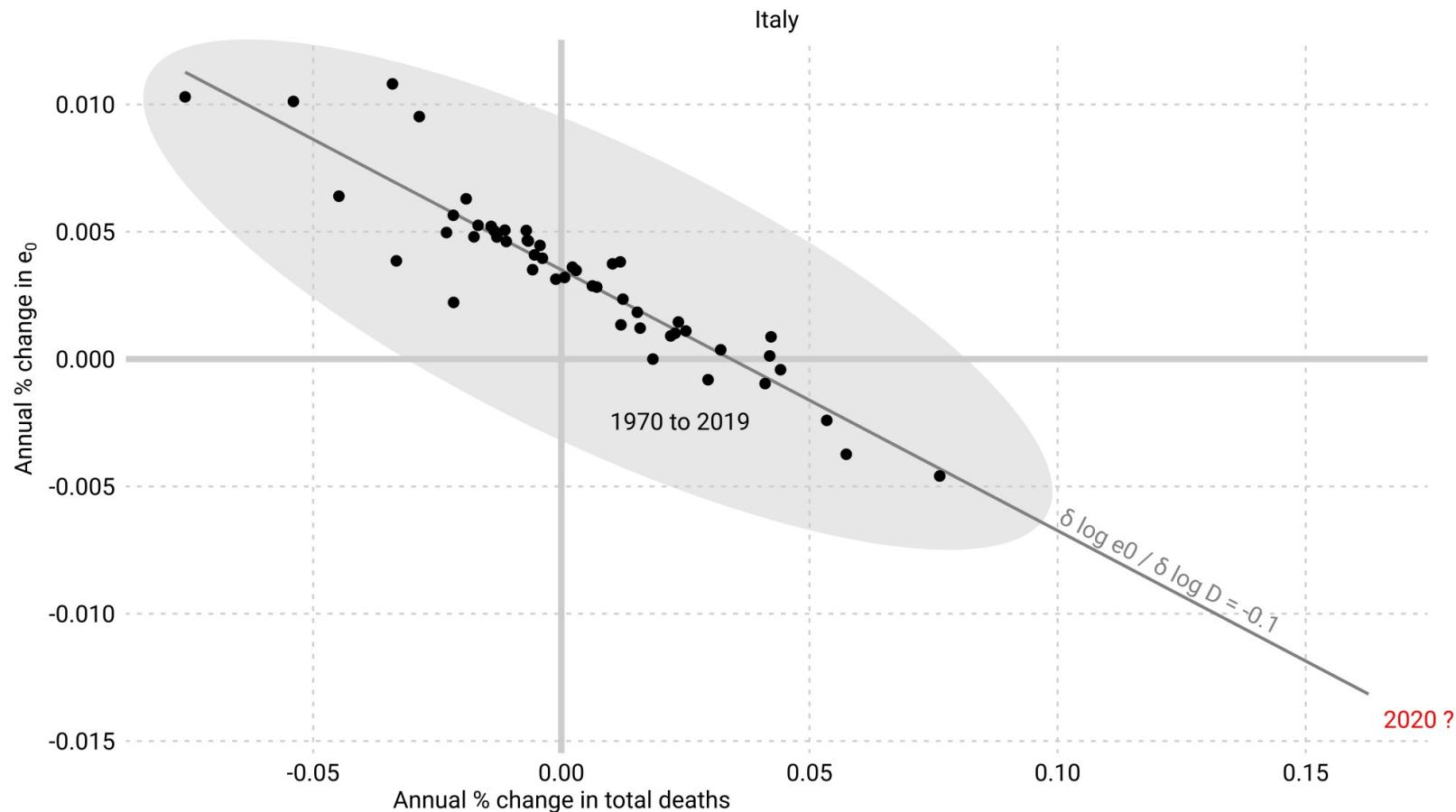
Predictive modeling in demography: Indirect estimation



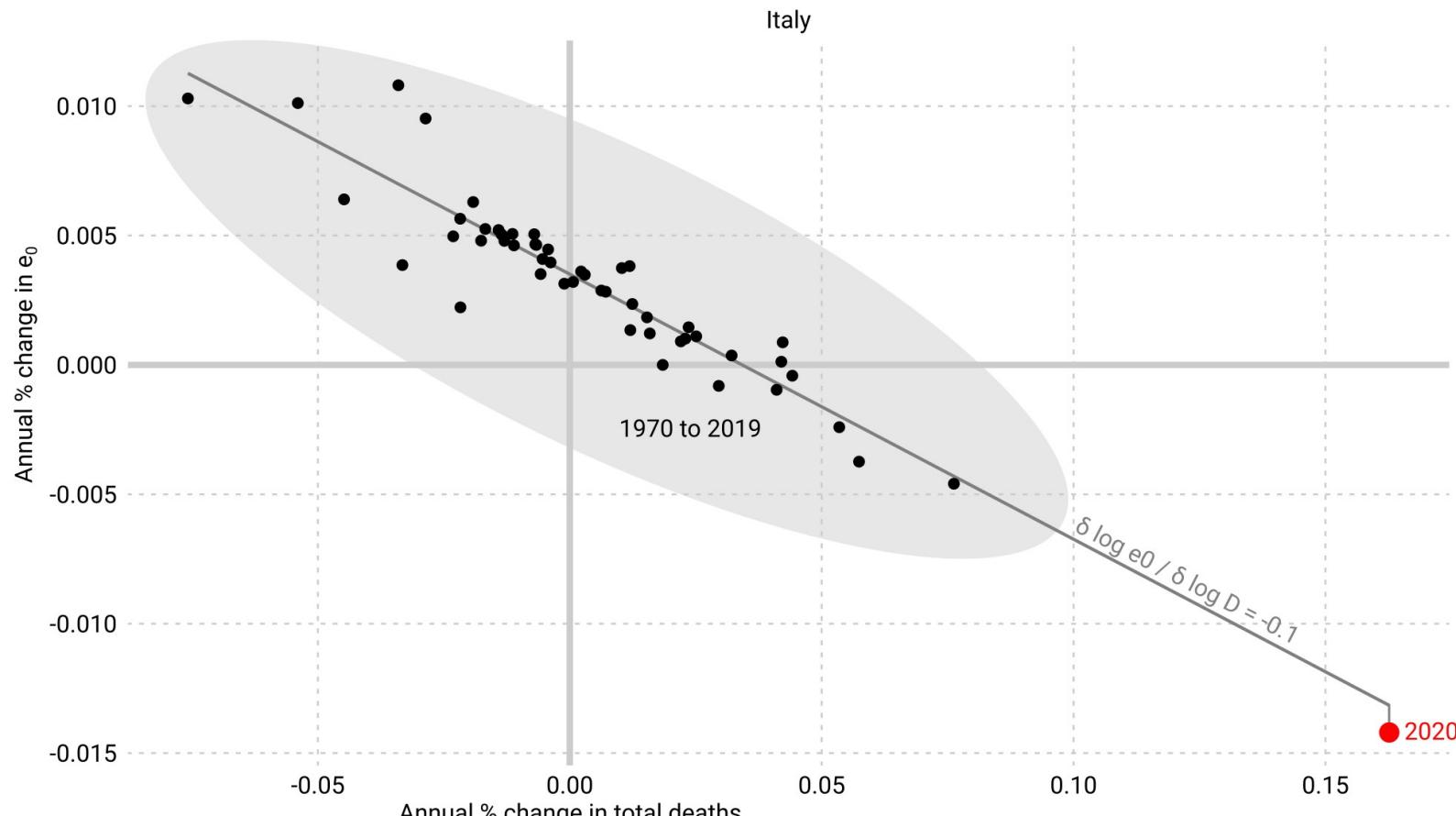
Predictive modeling in demography: Indirect estimation



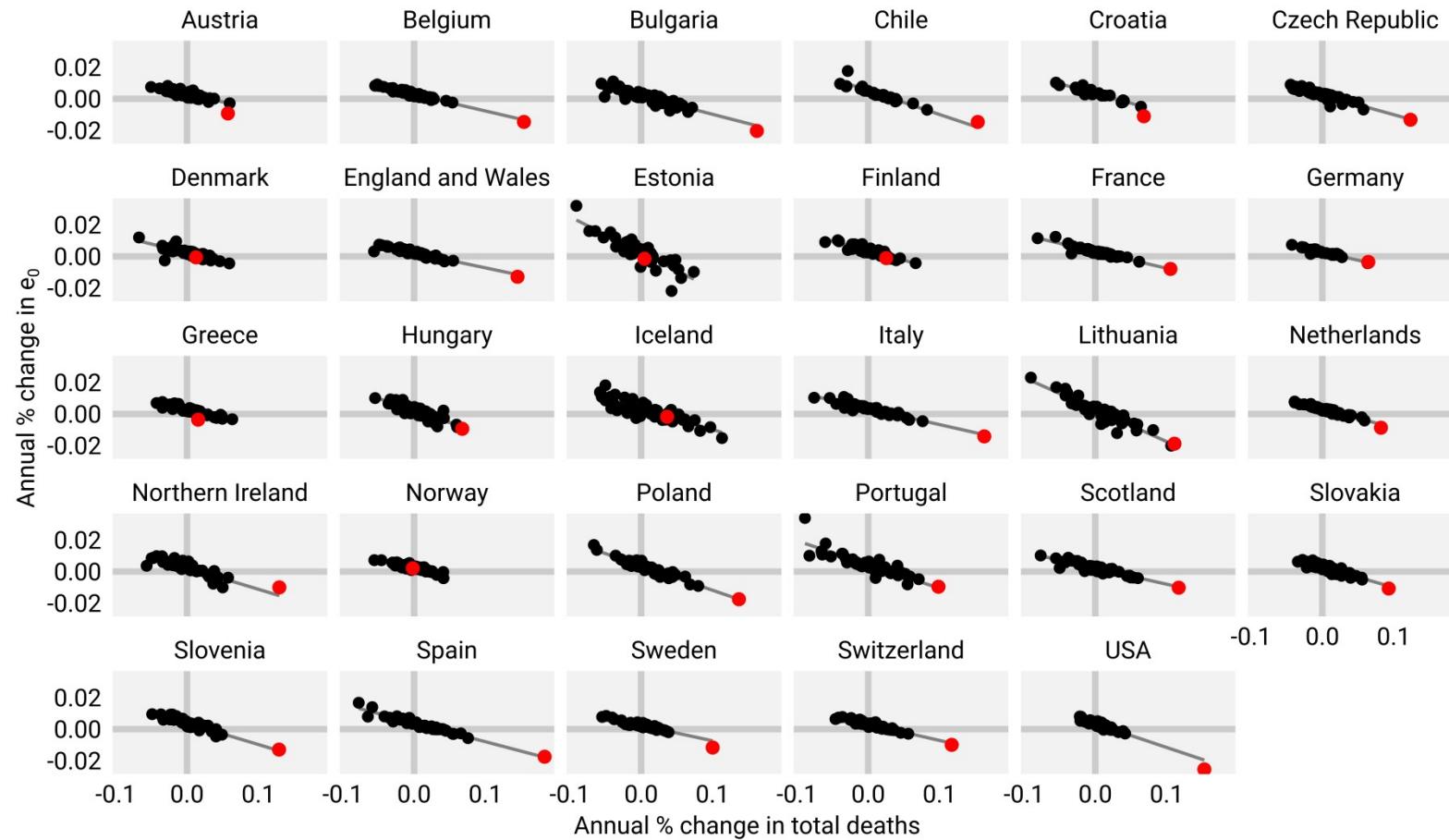
Predictive modeling in demography: Indirect estimation



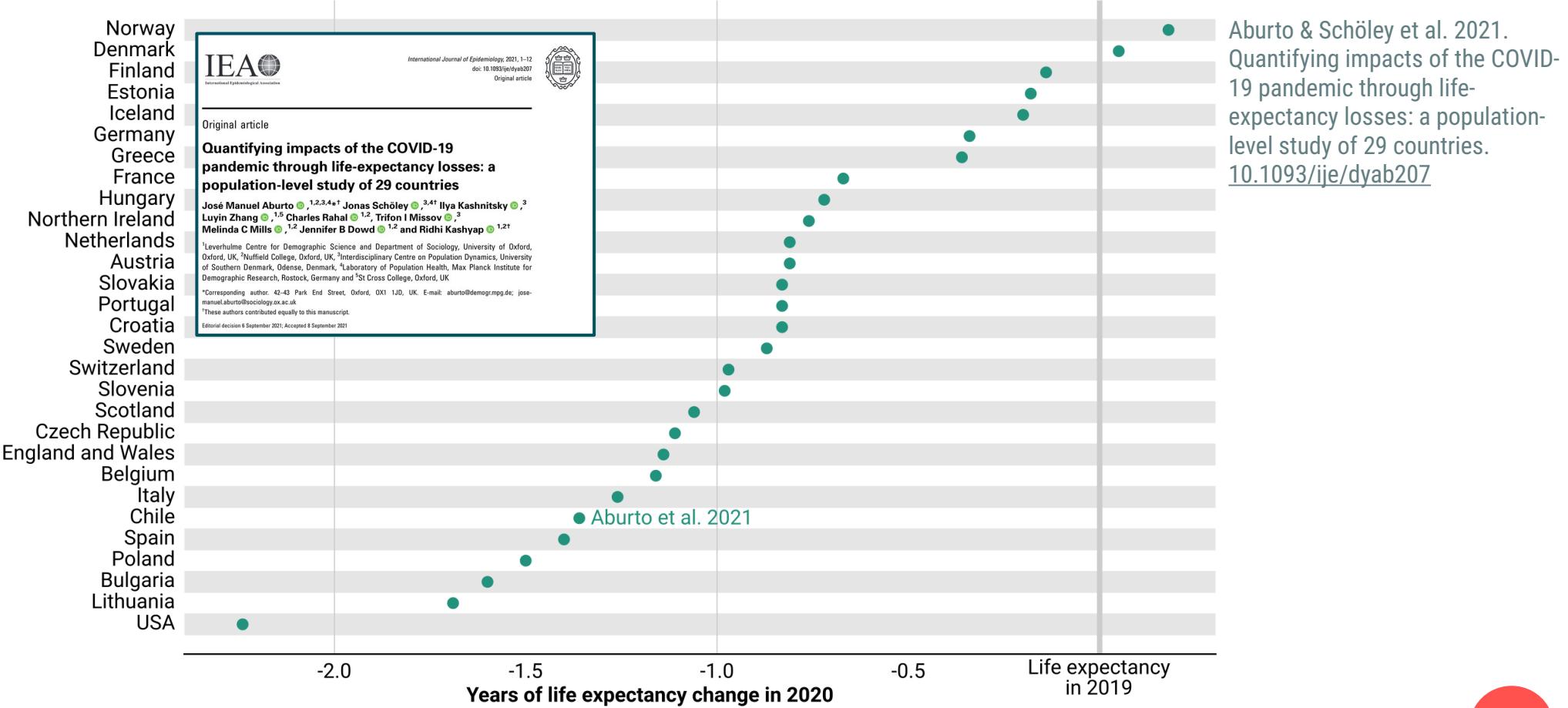
Predictive modeling in demography: Indirect estimation



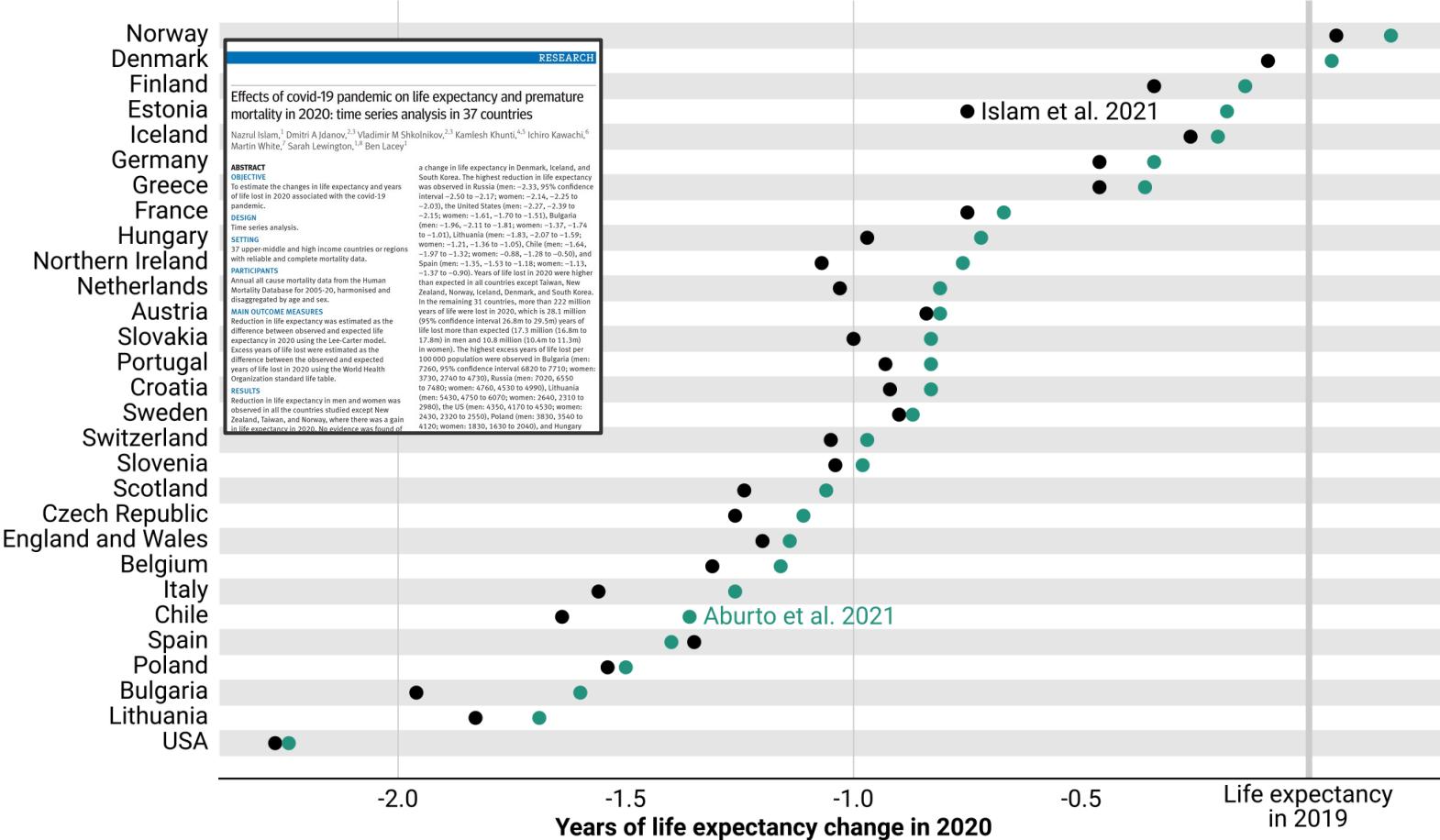
Predictive modeling in demography: Indirect estimation



Predictive modeling in demography: Indirect estimation



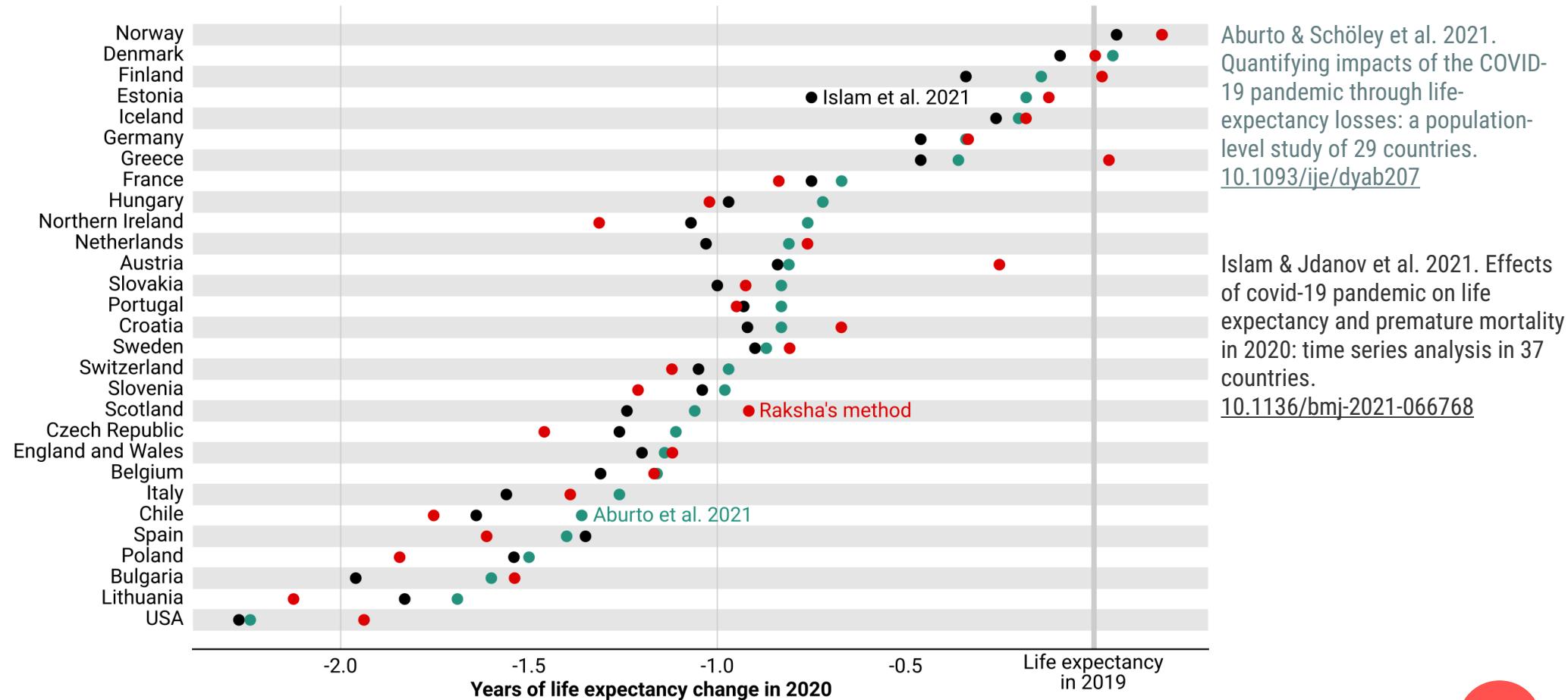
Predictive modeling in demography: Indirect estimation



Aburto & Schöley et al. 2021.
Quantifying impacts of the COVID-19 pandemic through life-expectancy losses: a population-level study of 29 countries.
[10.1093/ije/dyab207](https://doi.org/10.1093/ije/dyab207)

Islam & Jdanov et al. 2021. Effects of covid-19 pandemic on life expectancy and premature mortality in 2020: time series analysis in 37 countries.
[10.1136/bmj-2021-066768](https://doi.org/10.1136/bmj-2021-066768)

Predictive modeling in demography: Indirect estimation



Predictive modeling in demography: Indirect estimation



A radically simple way to monitor life expectancy

Ilya Kashnitsky & Alexey Raksha & Jose Manuel Aburto &
Jonas Schöley & James W. Vaupel

Jonas Schöley



@jschoeley



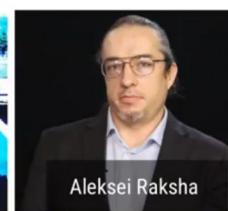
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Ilya Kashnitsky



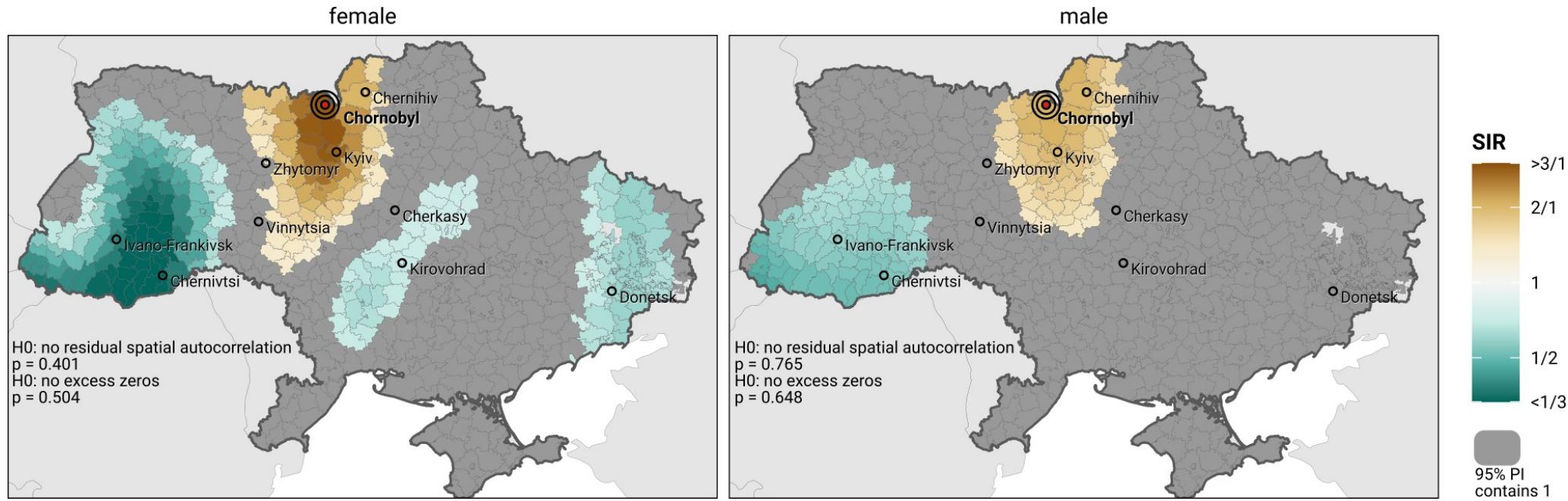
Aleksei Raksha



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Kashnitsky, Raksha, Schöley et al. (2021). Monitoring life expectancy. [Link to video](#)

Predictive modeling in demography: Spatial analyses



Levchuk, Schöley, Cilek, Jasilionis (2023). Long-term health effects of the Chernobyl accident.

Predictive modeling in demography: Projections and forecasts

The screenshot shows a news article from the German news channel 'tagesSchau'. The top left corner features the 'tagesSchau' logo with a blue circular icon containing a white '1'. To its right is the text 'Sendung verpasst?' with a play button icon. On the far right is a menu icon consisting of three horizontal lines. Below the header is a photograph of a modern building at night, with the words 'Deutsche Rentenversicherung' visible on the side of the building.

2,1 Milliarden Euro Überschuss

Rentenversicherung macht dickes Plus

Stand: 28.12.2022 05:11 Uhr

Zum Jahresende erwartet die gesetzliche Rentenversicherung einen Überschuss von 2,1 Milliarden Euro. Grund sei nicht nur ein stabiler Arbeitsmarkt. Eine höhere Sterblichkeit durch die Corona-Pandemie führe auch zu weniger Ausgaben.

Die gesetzliche Rentenversicherung erwartet zum Jahresende einen Überschuss von 2,1 Milliarden Euro. Das sagte die Präsidentin der Rentenversicherung, Gundula Roßbach, der Nachrichtenagentur dpa. "Vor einem Jahr war noch ein Defizit von 6,5 Milliarden Euro vorhergesagt worden."

Predictive modeling in demography: Projections and forecasts

The screenshot shows a news article from 'tagesSchau'. At the top left is the 'tagesSchau' logo. In the top right corner, there are buttons for 'Sendung verpasst?' (missed broadcast) and a menu icon. Below the header is a photograph of a building with a large blue sign that reads 'Deutsche Rentenversicherung'. The text below the photo states '2,1 Milliarden Euro Überschuss' (2.1 billion Euro surplus). The main title of the article is 'Rentenversicherung macht dickes Plus' (Pension insurance makes a big plus). Below the title is the text 'Stand: 28.12.2022 05:11 Uhr' (Stand: 28.12.2022 05:11 AM). The article text discusses the expected surplus of 2.1 billion Euro due to a stable labor market and lower mortality rates due to the COVID-19 pandemic.

2,1 Milliarden Euro Überschuss

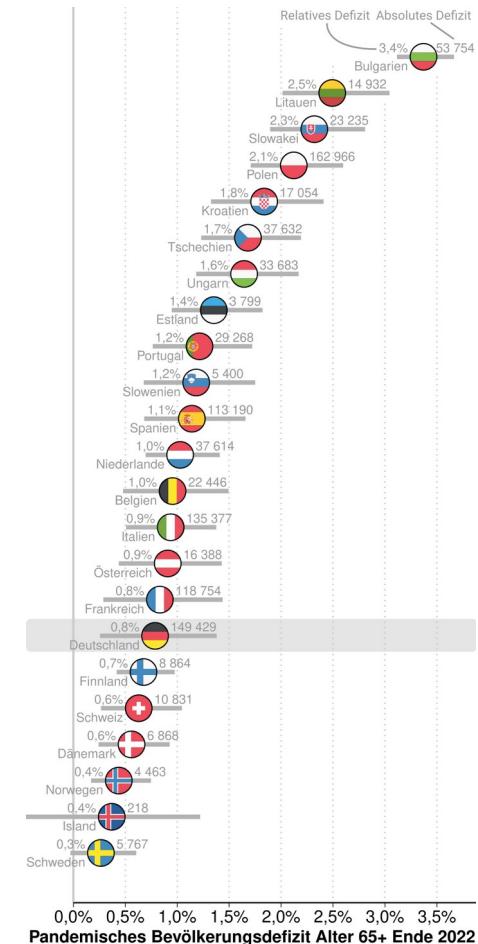
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Schöley (2023). Bevölkerungsalterung unter Pandemiebedingungen.

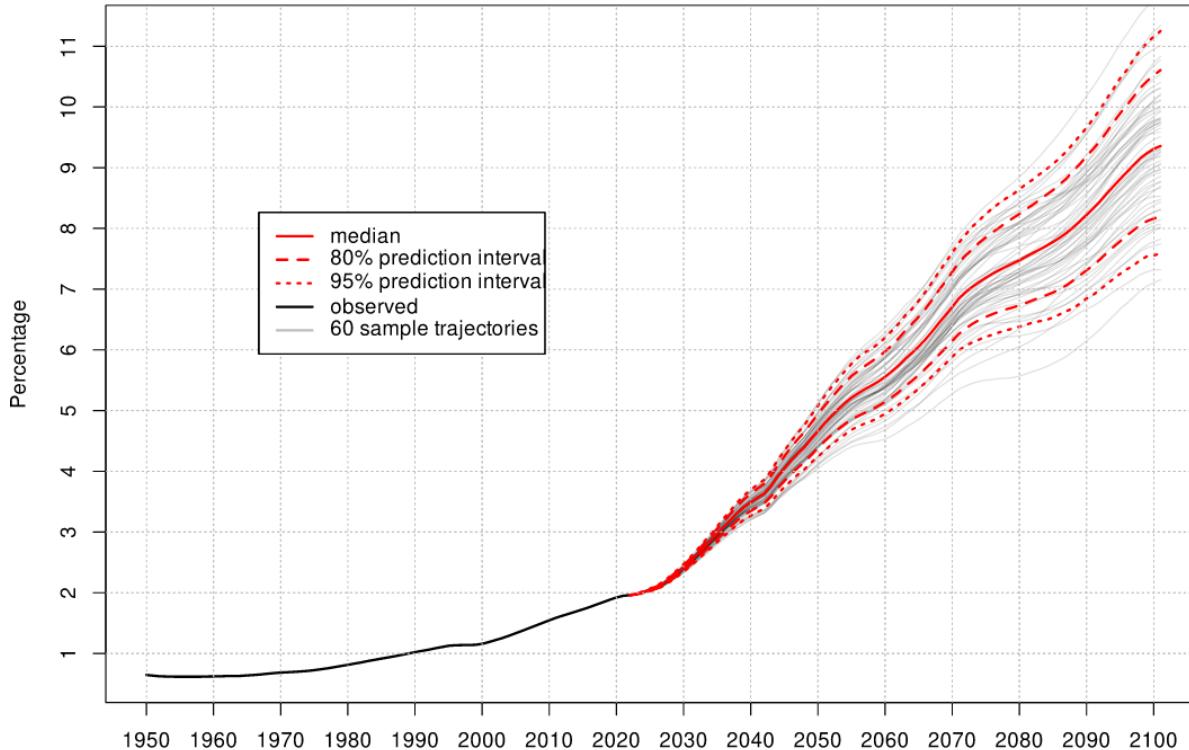


Predictive modeling in demography: Projections and forecasts

World: Percentage of population aged 80 years or over



Department of Economic and Social Affairs
Population Division

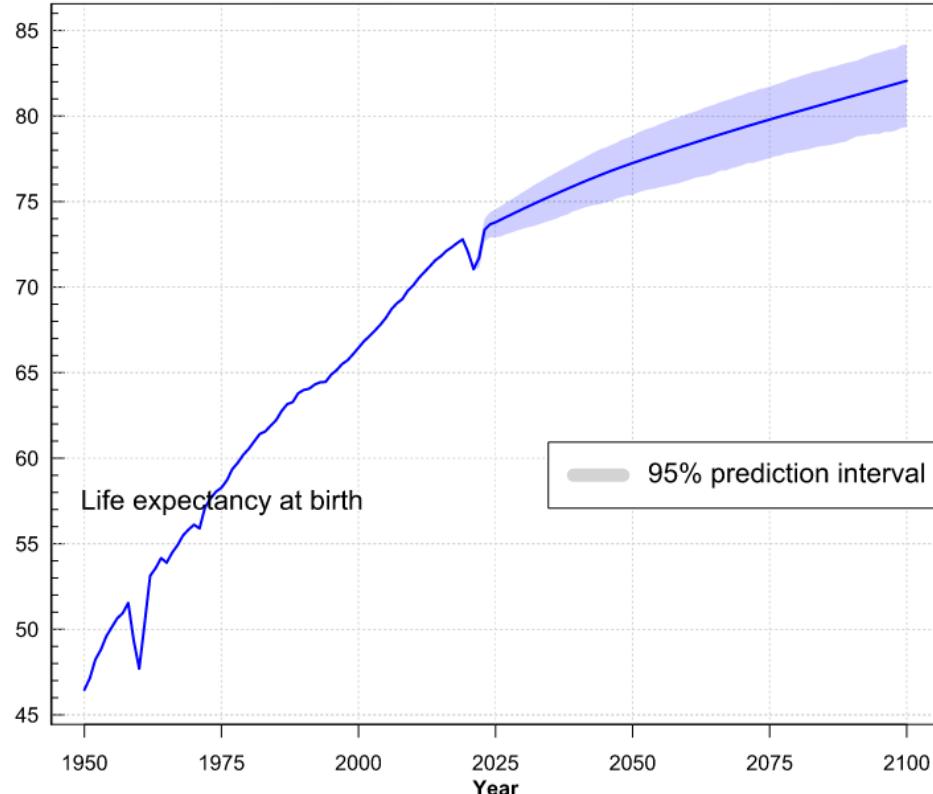


© 2022 United Nations, DESA, Population Division. Licensed under Creative Commons license CC BY 3.0 IGO.
United Nations, DESA, Population Division. *World Population Prospects 2022*. <http://population.un.org/wpp/>

UN (2022). World Population Prospects. [Web link](#).

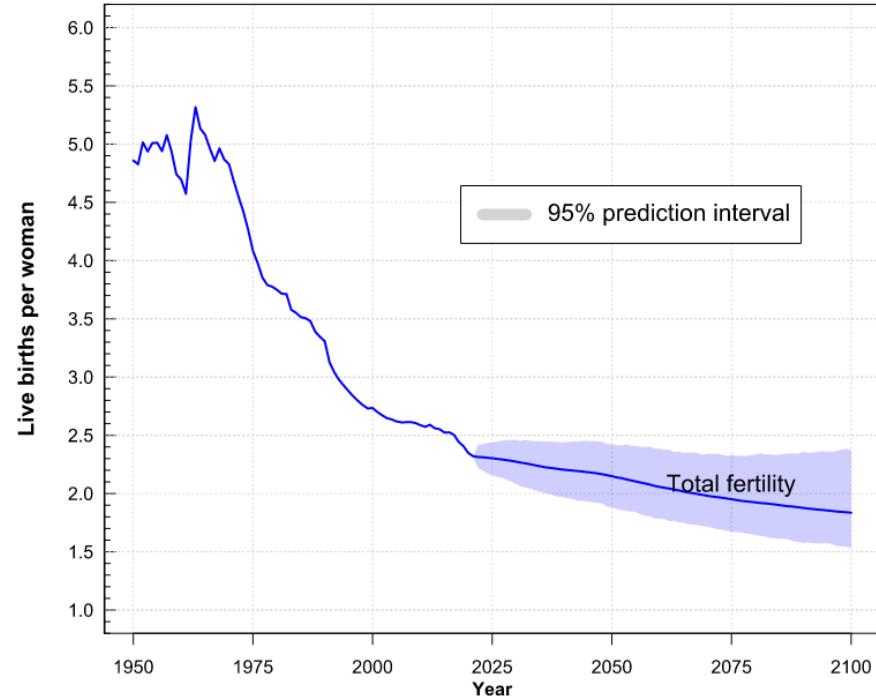
Predictive modeling in demography: Projections and forecasts

Life expectancy at birth (both sexes combined)



Department of Economic and Social Affairs
Population Division

Total fertility



Predictive modeling in demography: Projections and forecasts

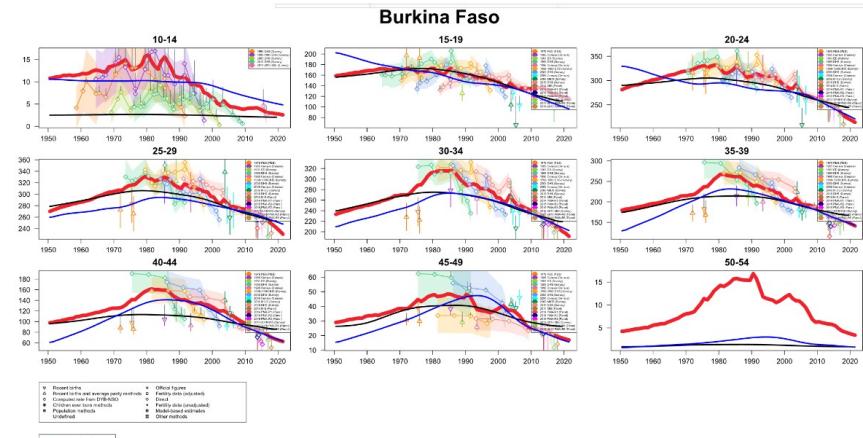
Population projection Cohort component / Leslie

$$\begin{pmatrix} n_0 \\ n_1 \\ n_2 \\ n_3 \\ \vdots \\ n_{\nu-1} \end{pmatrix}_{t+1} = \begin{pmatrix} f_0 & f_1 & f_2 & \dots & f_{\nu-2} & f_{\nu-1} \\ s_0 & 0 & 0 & \dots & 0 & 0 \\ 0 & s_1 & 0 & \dots & 0 & 0 \\ 0 & 0 & s_2 & \dots & 0 & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & \dots & s_{\nu-2} & 0 \end{pmatrix} \cdot \begin{pmatrix} n_0 \\ n_1 \\ n_2 \\ n_3 \\ \vdots \\ n_{\nu-1} \end{pmatrix}_t$$

+ Net-migration by age



Baseline population estimates

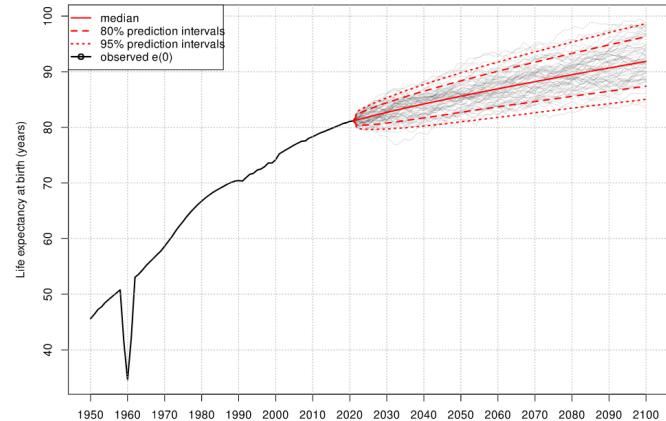


Fertility forecasts



Department of Economic and Social Affairs
Population Division

Figure II.6
Estimates and projected probabilistic trajectories of female life expectancy at birth, China, 1950-2100 (years)



Life-expectancy forecasts with derived mortality by age

UN (2022). World Population Prospects. [Web link](#).

Predictive modeling in demography: Projections and forecasts



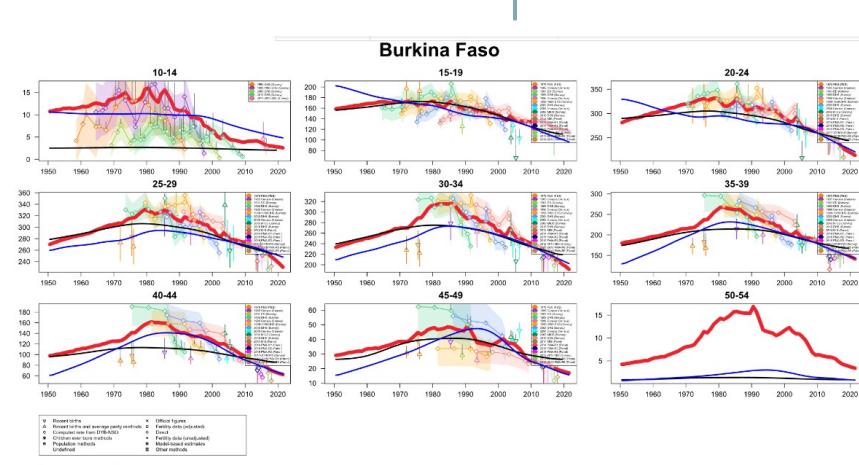
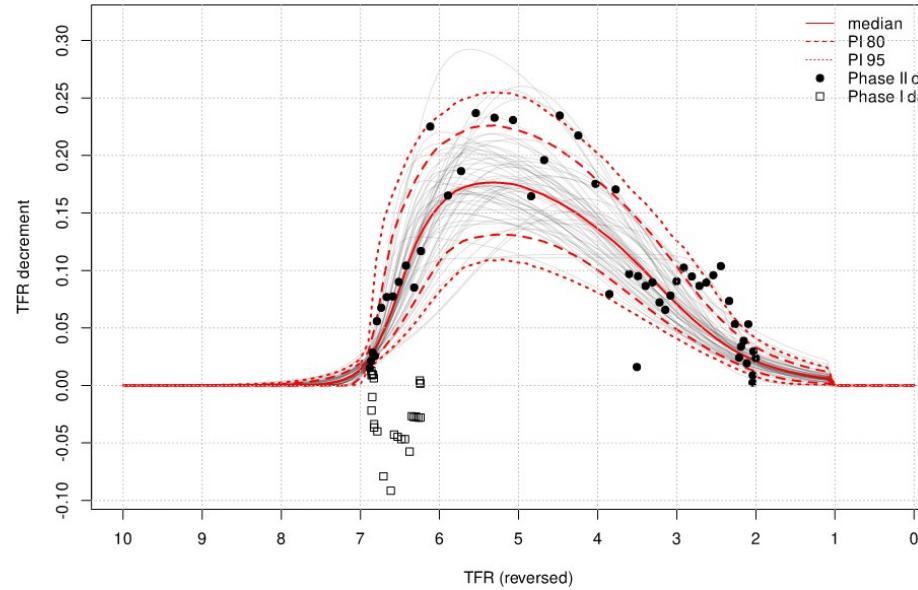
Department of Economic and Social Affairs
Population Division

$$\begin{pmatrix} n_0 \\ n_1 \\ n_2 \\ n_3 \\ \vdots \\ n_{\nu-1} \end{pmatrix}_{t+1} = \begin{pmatrix} f_0 & f_1 & f_2 & \dots & f_{\nu-2} & f_{\nu-1} \\ s_0 & 0 & 0 & \dots & 0 & 0 \\ 0 & s_1 & 0 & \dots & 0 & 0 \\ 0 & 0 & s_2 & \dots & 0 & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & \dots & s_{\nu-2} & 0 \end{pmatrix} \cdot \begin{pmatrix} n_0 \\ n_1 \\ n_2 \\ n_3 \\ \vdots \\ n_{\nu-1} \end{pmatrix}_t$$

Figure II.6
Estimates and projected probabilistic trajectories of female life expectancy at birth, China, 1950-2100 (years)

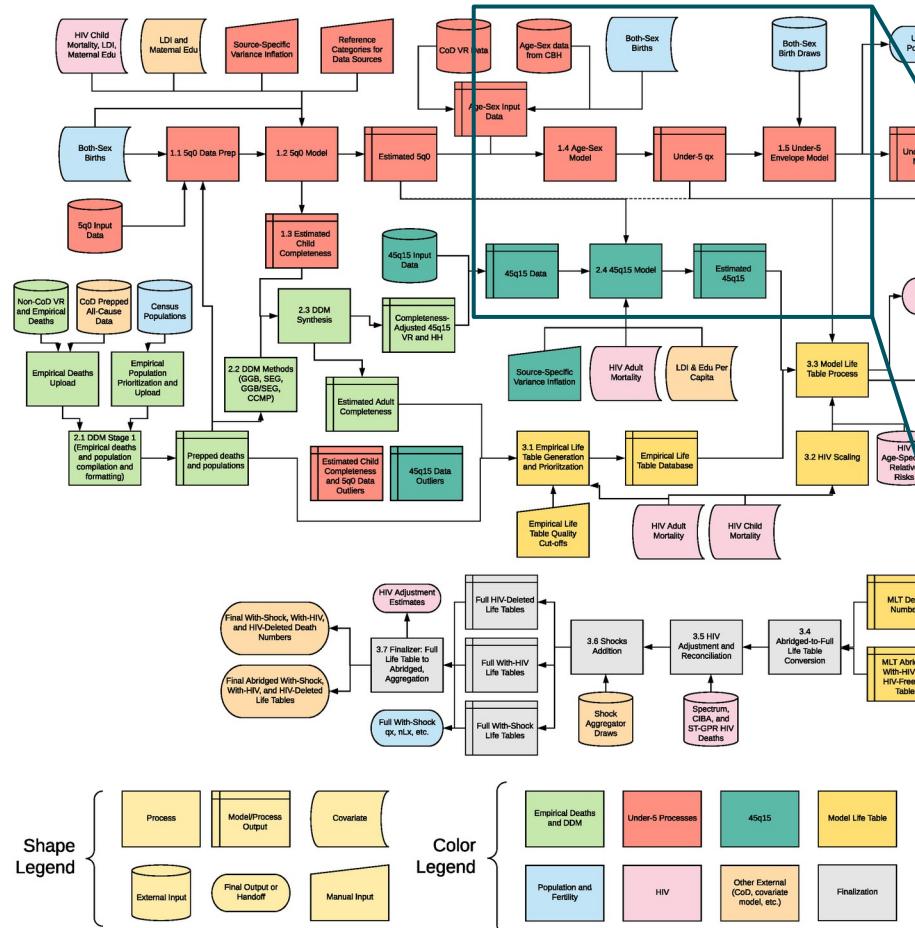


Figure II.2
Total fertility annual decrements by level of fertility and prediction intervals of estimated double-logistic curve for Bangladesh (systematic decline part) (live births per woman)

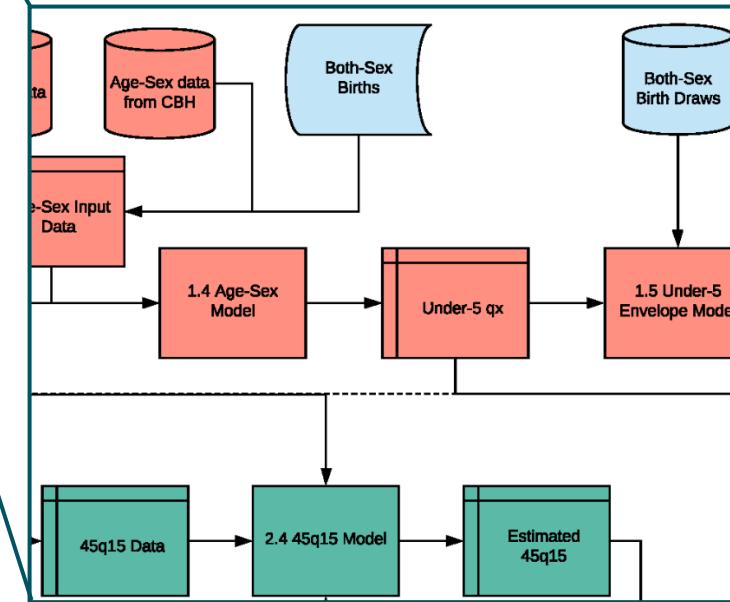


Fertility forecasts

Predictive modeling in demography: Projections and forecasts



Global Burden of Disease (2019).
Mortality 1 Estimation Flowchart. [Web link](#).



Predictive modeling in demography: Indirect estimation

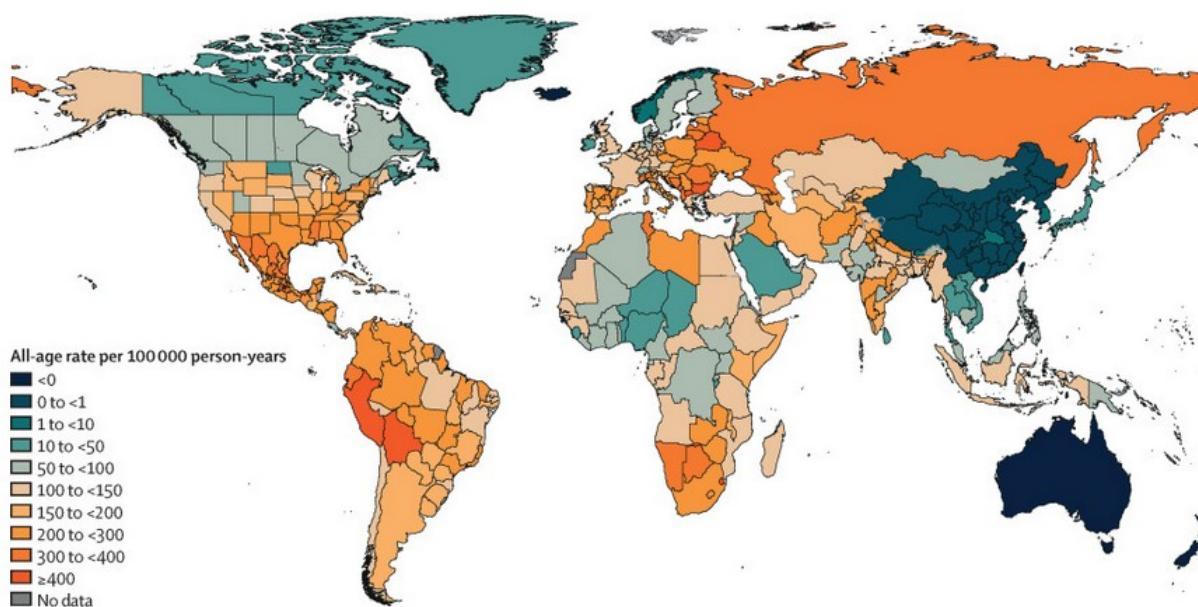
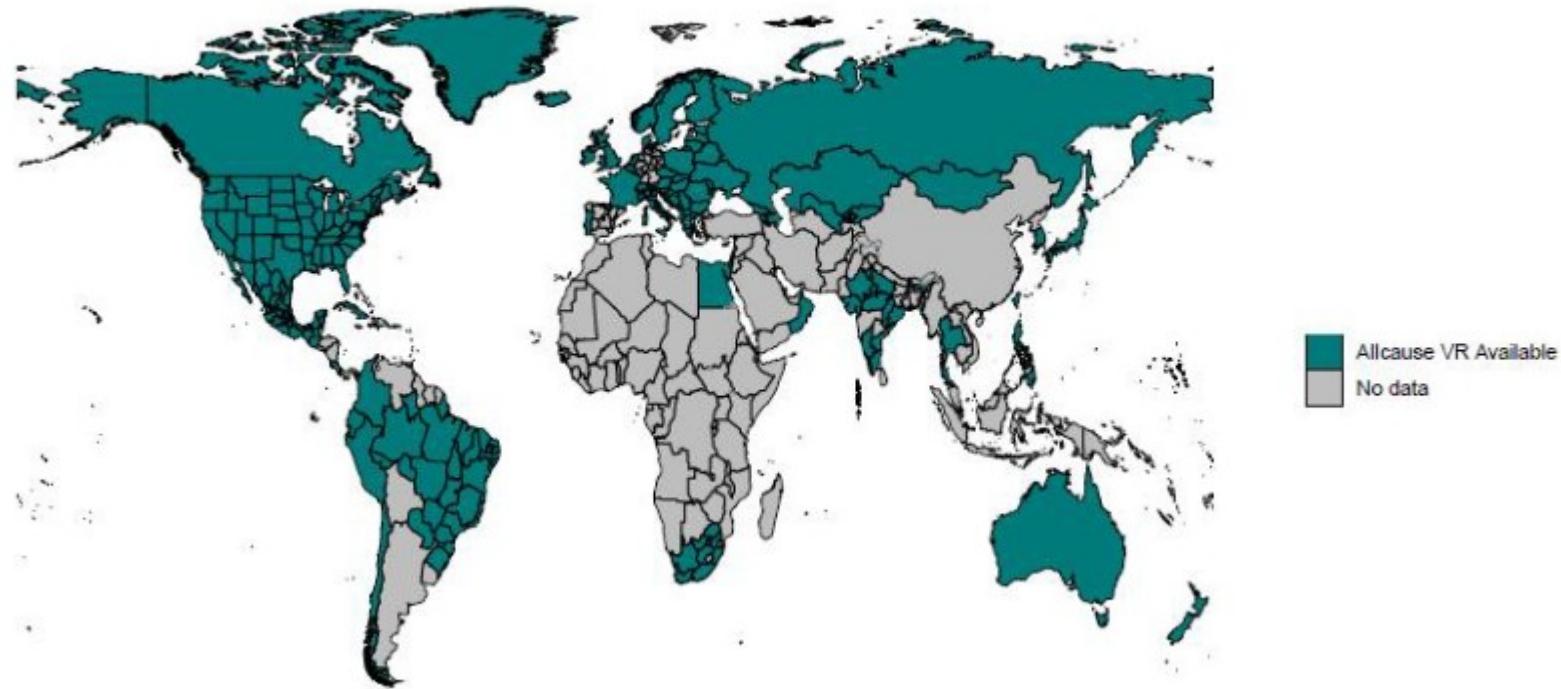


Figure 2. Global distribution of estimated excess mortality rate due to the COVID-19 pandemic, for the cumulative period 2020–21

COVID-19 Excess Mortality Collaborators (2022). Estimating excess mortality... [10.1016/S0140-6736\(21\)02796-3](https://doi.org/10.1016/S0140-6736(21)02796-3)

Predictive modeling in demography: Indirect estimation

Figure S1. Map of all cause data availability



COVID-19 Excess Mortality Collaborators (2022). Estimating excess mortality... [Link to Supplementary](#)

Predictive modeling in demography: Indirect estimation

Figure S1. Map of all cause data availability

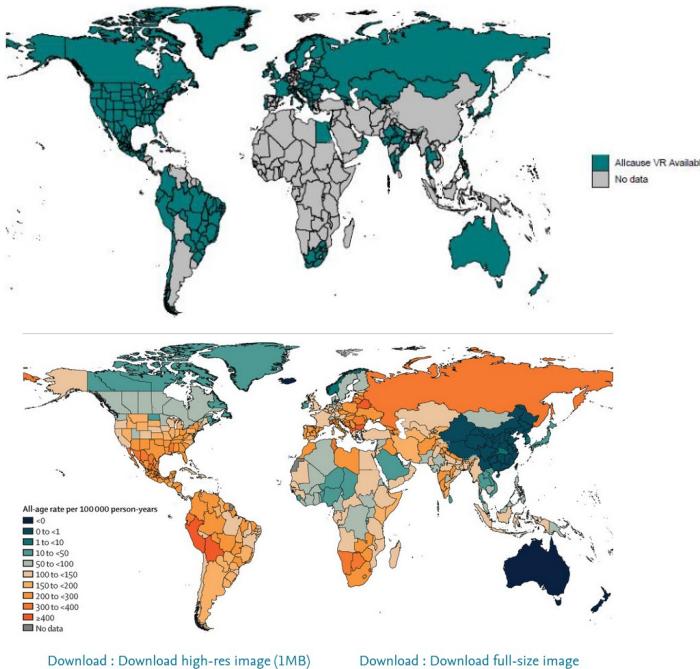


Figure 2. Global distribution of estimated excess mortality rate due to the COVID-19 pandemic, for the cumulative period 2020–21

To arrive at a parsimonious model, we used the Least Absolute Shrinkage and Selection Operator (LASSO) regression to help select a list of covariates that have sensible direction of effect on the excess mortality rate due to the COVID-19 pandemic. The final model can be described by the equation below:

$$\ln(y_i) = \alpha + \sum_{j=1}^{16} \beta_j \cdot x_{ij} + \epsilon_i$$

Average absolute latitude		Positive
Cardiovascular diseases death rate (2019)	Log	Positive
Crude death rate (2019)	Log	Positive
Diabetes death rate (2019)	Log	Positive
Healthcare access and quality Index (2019)		Negative
HIV death rate (2019)	Log	Positive
Infection detection ratio (lagged)		Negative
Inpatient admission rate (2019)		Negative
Mobility (lagged)		Positive
Proportion of population over age 75		Positive
Quality of death registration system (2019)		Negative
Reported COVID-19 death rate	Log	Positive
Seroprevalence rate (lagged)	Log	Positive
Smoking prevalence (2019)		Positive
Universal health coverage (2019)		Negative

COVID-19 Excess Mortality Collaborators (2022). Estimating excess mortality... [Link to Supplementary](#)
github.com/ihmeuw-demographics/publication_covid_em/tree/main/03_ensemble_excess_model

Parameter-centric modeling vs. predictive modeling

$f(y|x, \theta)$

VS.

$f(y|x, \theta)$

Predictive modeling workflow

$$f(y|x, \theta)$$

Predict from model

Transform model predictions

Propagate prediction uncertainty through analysis

Cross-validate predictive accuracy & model calibration

Predict from model

Predict from model – The model equation

$$D_t \sim \text{NegBin}(\mu_t, \theta)$$

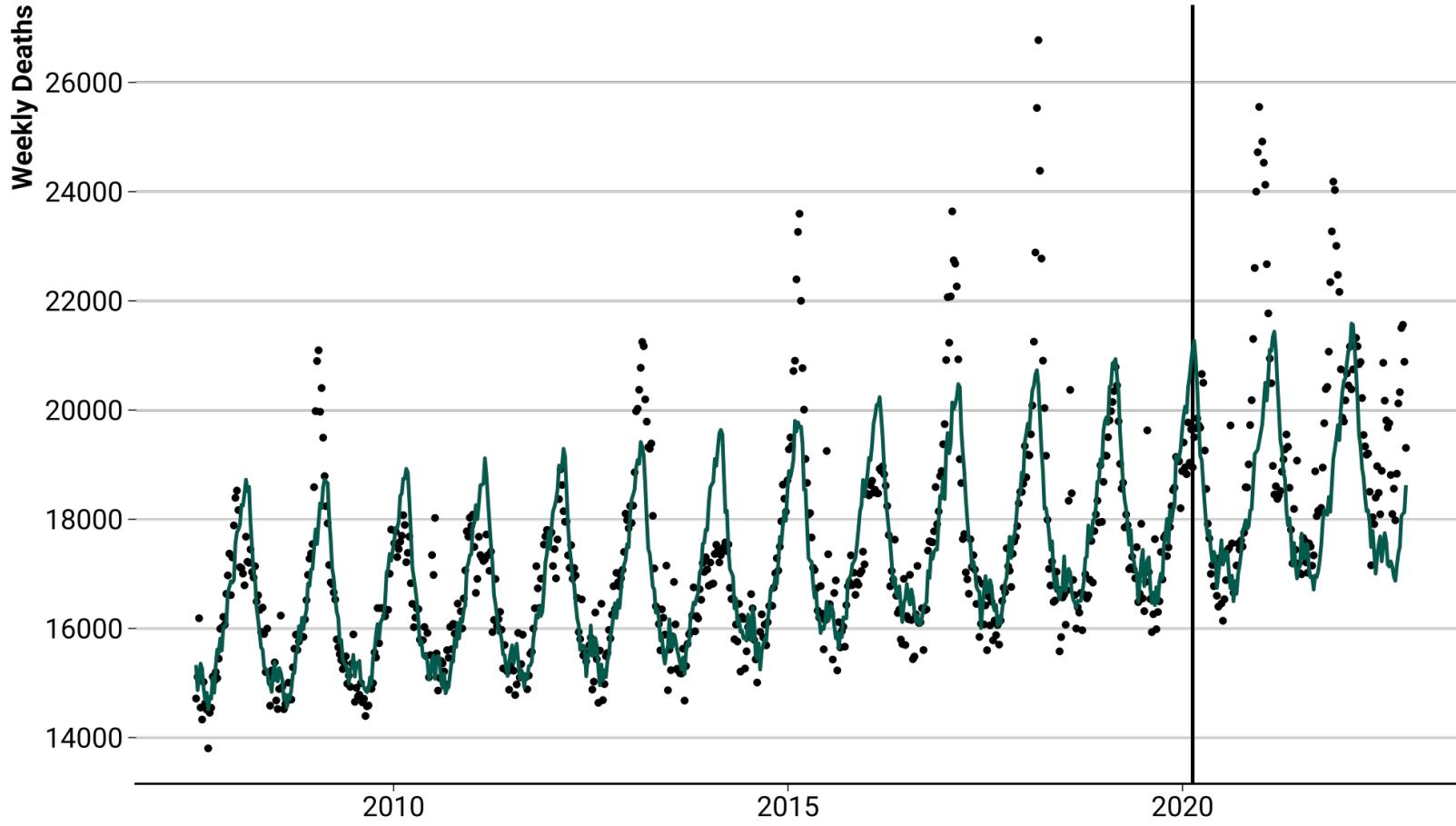
$$\mu_t = \exp(\beta_0 + \beta_y \text{year}_t + \sum_{i=1:52} \beta_{w[i]} \text{week}_t + \log(\text{population}_t))$$

$$\theta = \exp(\beta_\theta)$$

Observations
Sampling Distribution
Parameters
Predictors

Predict from model – Point estimates

Observed vs. expected weekly deaths Germany



Transform model predictions

Transform model predictions

$$D_t \sim \text{NegBin}(\mu_t, \theta)$$

$$\mu_t = \exp(\beta_0 + \beta_y \text{year}_t + \sum_{i=1:52} \beta_{w[i]} \text{week}_t + \log(\text{population}_t))$$

$$\theta = \exp(\beta_\theta)$$

Cumulative excess deaths:

$$\sum_t D_t - \mu_t$$

Transform model predictions

Cumulative weekly excess deaths Germany



Propagate prediction uncertainty through analysis

Propagate uncertainty

How many deaths in a week had C19 not occurred?

$$\text{Excess} = \text{Observed} - \text{Expected}$$

Propagate uncertainty

How many deaths in a week had C19 not occurred?

$$\text{Excess} = \text{Observed} - \text{Expected}$$

Propagate uncertainty

How many deaths in a week had C19 not occurred?

$$\text{Excess} = \text{Observed} - \text{Expected}$$

Propagate uncertainty – Epistemic uncertainty

$$D_t \sim \text{NegBin}(\mu_t, \theta)$$

$$\mu_t = \exp(\beta_0 + \beta_y \text{year}_t + \sum_{i=1:52} \beta_{w[i]} \text{week}_t + \log(\text{population}_t))$$

$$\theta = \exp(\beta_\theta)$$

Uncertainty regarding the state of the world, here:

Uncertain parameter estimates

Family:	Negative Binomial(404.799)									
Link function:	log									
Formula:										
deaths_observed ~ iso_year + iso_week_fct + offset(log(personweeks))										
Parametric coefficients:										
	Estimate	Std. Error	z value	Pr(> z)						
(Intercept)	-2.427e+01	1.102e+00	-22.028	< 2e-16 ***						
iso_year	7.886e-03	5.471e-04	14.413	< 2e-16 ***						
iso_week_fct2	1.002e-02	2.051e-02	0.489	0.62508						
iso_week_fct3	7.545e-03	2.051e-02	0.368	0.71298						
iso_week_fct4	1.041e-02	2.051e-02	0.508	0.61167						
iso_week_fct5	3.438e-02	2.051e-02	1.677	0.09364 .						
iso_week_fct6	3.924e-02	2.051e-02	1.913	0.05570 .						
iso_week_fct7	5.035e-02	2.051e-02	2.455	0.01408 *						
iso_week_fct8	5.995e-02	2.051e-02	2.880	0.00308 **						

Hüllermeier (2021). Aleatoric and epistemic uncertainty in machine learning... [10.1007/s10994-021-05946-3](https://doi.org/10.1007/s10994-021-05946-3)

Propagate uncertainty – Epistemic uncertainty

7.5.2 The delta method

The delta method provides an easy approximation for the confidence limits on values that are not parameters of the model. To use it you must have a formula for $\mu = f(a, b)$ that you can differentiate with respect to a and b . Unlike the first likelihood profile method, you don't have to be able to solve the equation for one of the parameters.

The formula for the delta method comes from a Taylor expansion of the formula for μ , combined with the definitions of the variance ($V(a) = E[(a - \bar{a})^2]$) and covariance ($C(a, b) = E[(a - \bar{a})(b - \bar{b})]$):

$$V(f(a, b)) \approx V(a) \left(\frac{\partial f}{\partial a} \right)^2 + V(b) \left(\frac{\partial f}{\partial b} \right)^2 + 2C(a, b) \frac{\partial f}{\partial a} \frac{\partial f}{\partial b}. \quad (7.5.4)$$

See the Appendix, or Lyons (1991) for a derivation and details.

7.5.4 Bayesian analysis

Finally, you can use a real Bayesian method: construct either an exact Bayesian model, or, more likely, a Markov chain Monte Carlo analysis for the parameters. Then you can calculate the posterior distribution of any function of the parameters (such as the mean survival time) from the posterior samples of the parameters, and get the 95% credible interval.

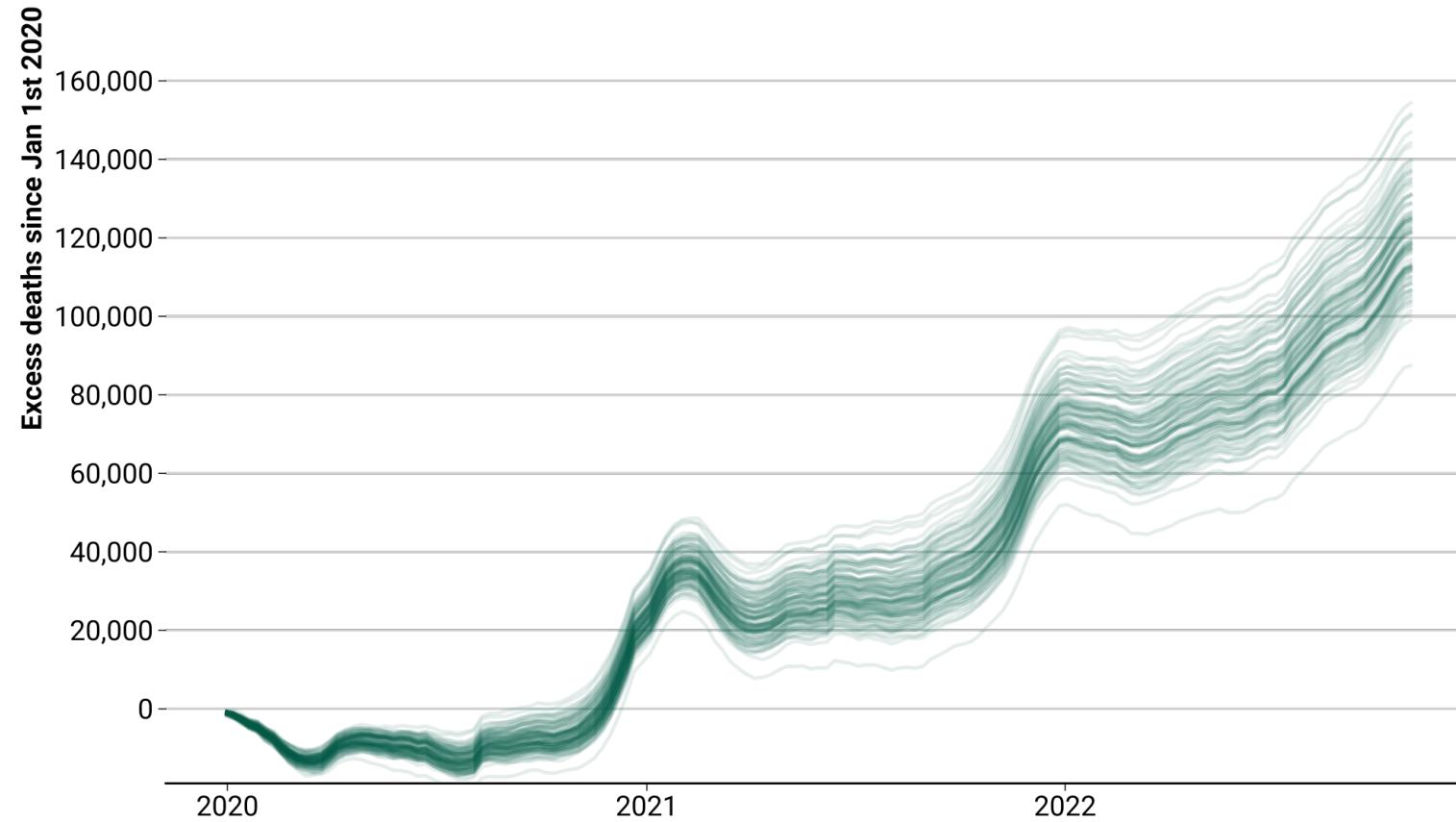
7.5.3 Population prediction intervals (PPI)

Another simple procedure for calculating confidence limits is to draw random samples from the estimated sampling distribution (approximated by the information matrix) of the parameters. In the approximate limit where the information matrix approach is valid, it turns out that the distribution of the parameters will be multivariate normal with a variance-covariance matrix given by the inverse of the information matrix. The MASS package in R has a function, `mvrnorm`*, for selecting multivariate normal random deviates. With the `mle2` fit `w1` from above, then

```
> vmat = mvrnorm(1000, mu = coef(w1), Sigma = vcov(w1))
```

Propagate uncertainty – Epistemic uncertainty

Cumulative weekly excess deaths Germany



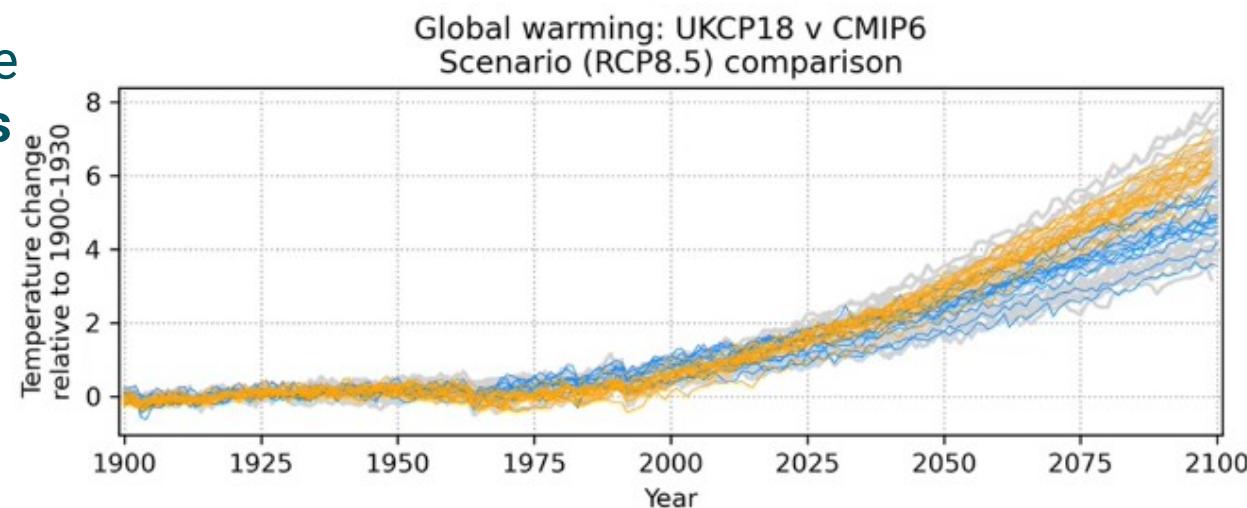
Uncertainty in model parameters propagated through transformed model predictions via sampling from Multivariate Normal approx. to sampling distribution of beta's

Propagate uncertainty – Epistemic uncertainty

Uncertainty regarding the state of the world, here:
Uncertain model structure

Uncertainties in projected changes

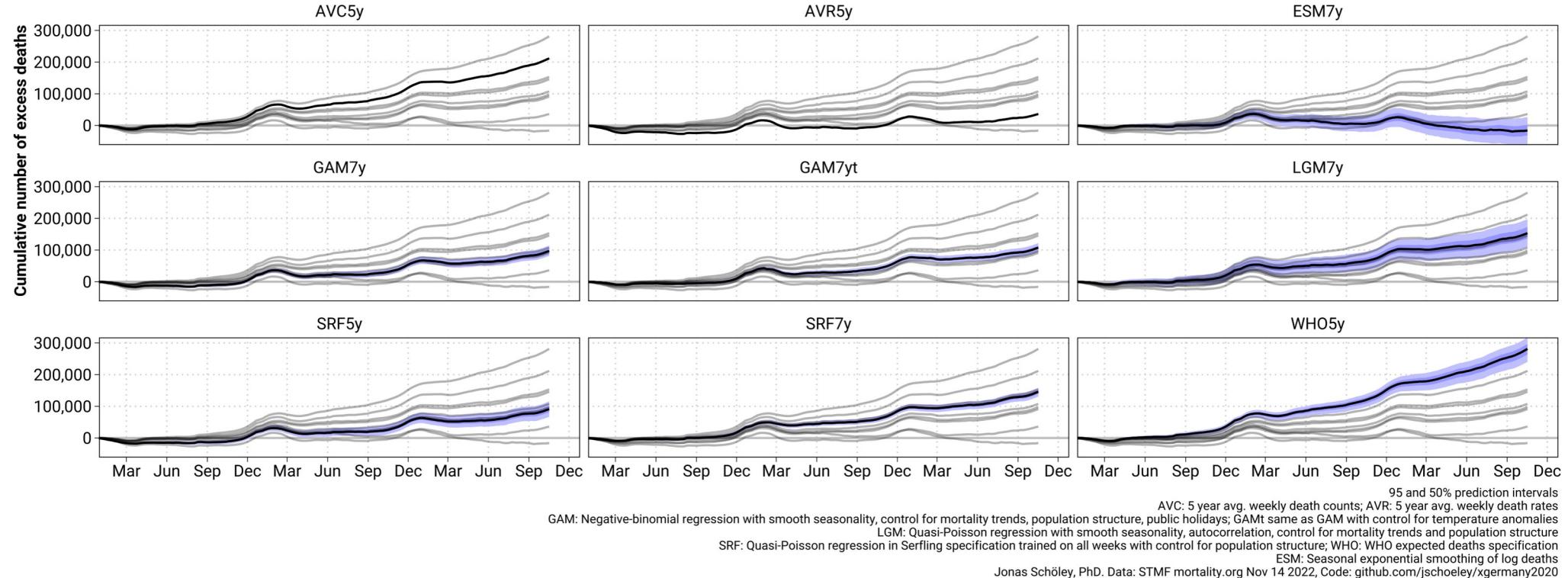
Internal variability and modelling uncertainty



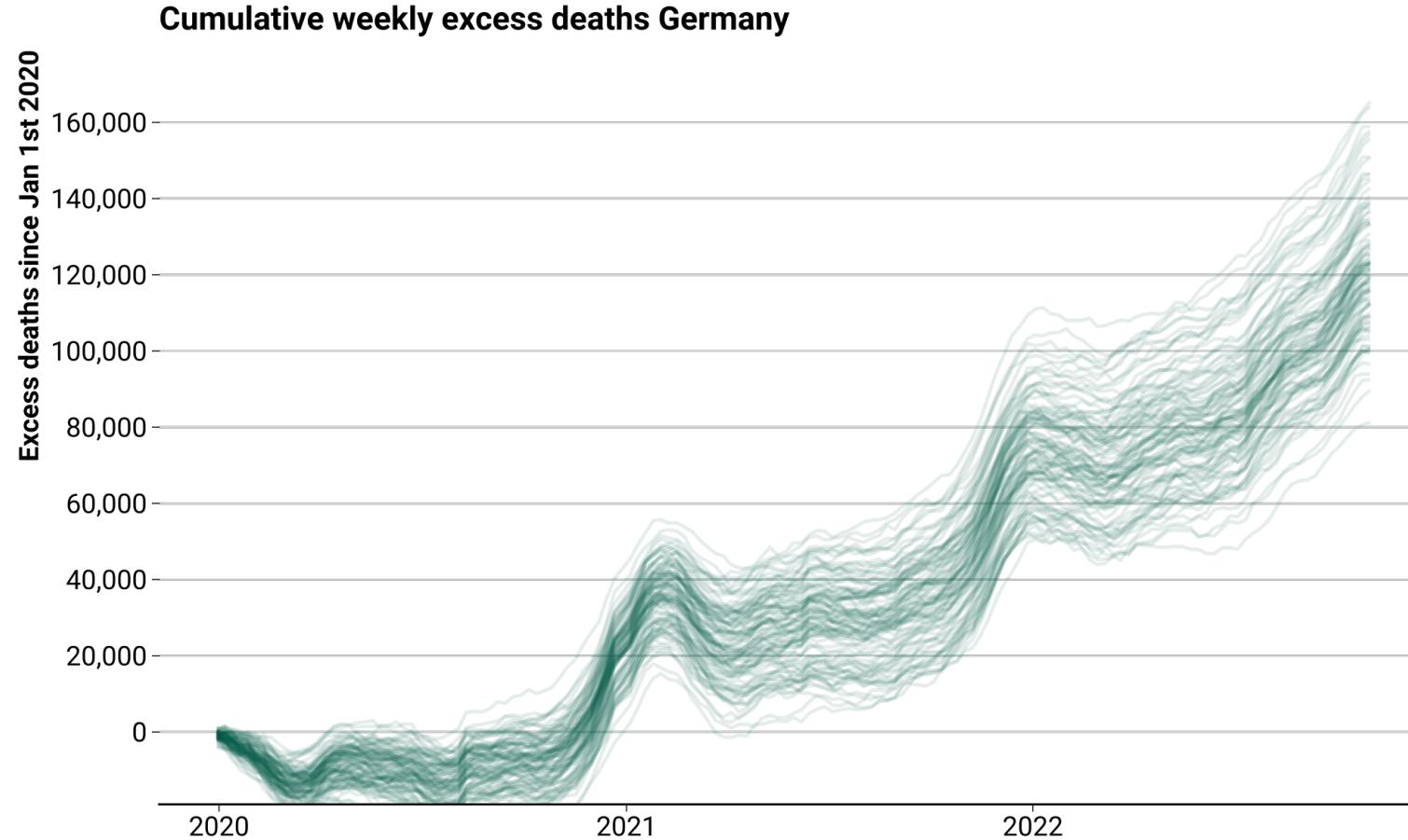
Murphy (2022). Informing risks and decisions using the UK climate projections. youtu.be/uiSTmy1vqls

Propagate uncertainty – Epistemic uncertainty

Cumulative excess deaths Germany 2020w1 through 2022 under different baseline models



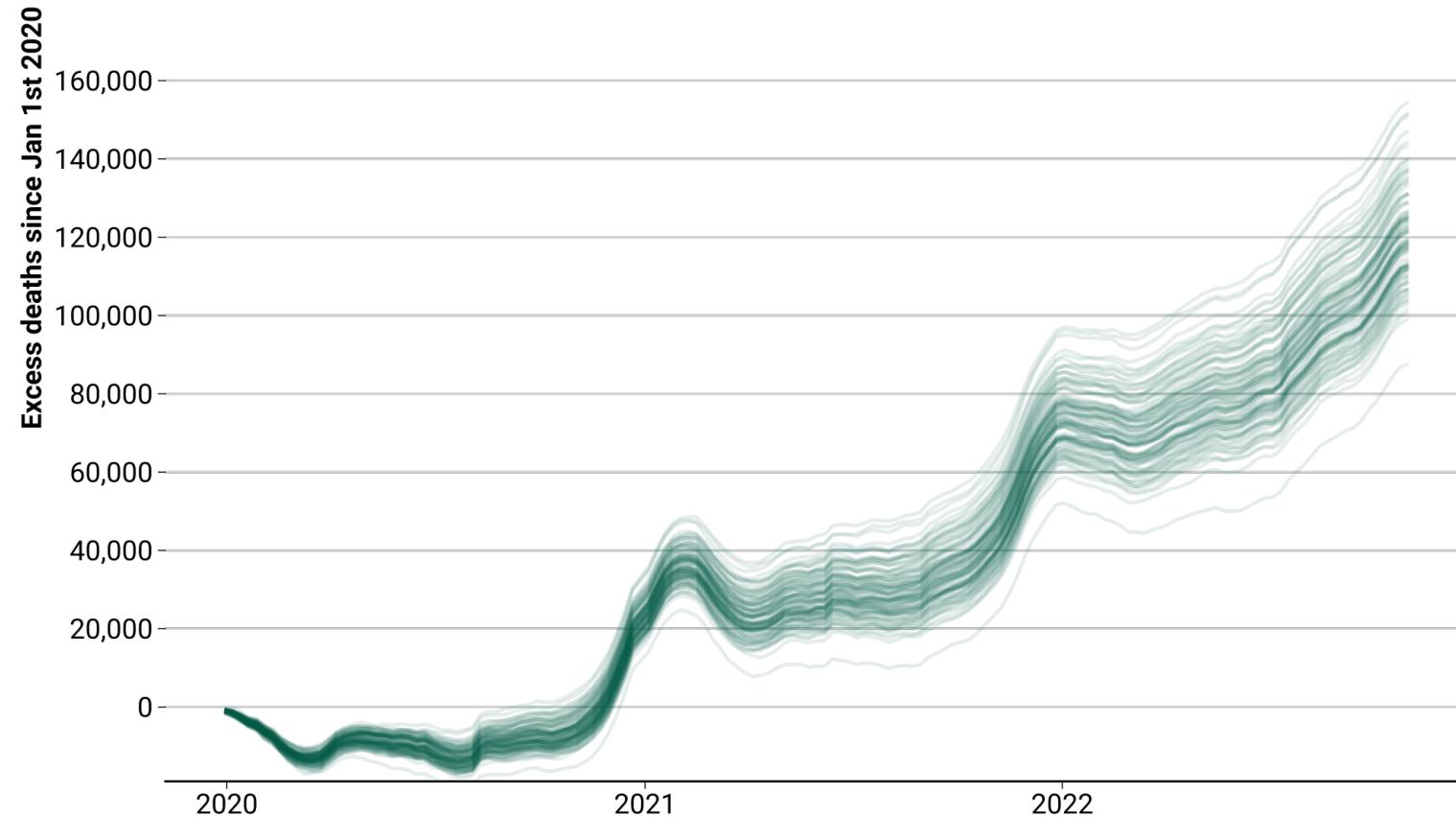
Propagate uncertainty – Aleatoric uncertainty



Given the sampled model parameters, draw samples from the outcome distribution (Negative-Binomial in this case).

Propagate uncertainty – Aleatoric uncertainty

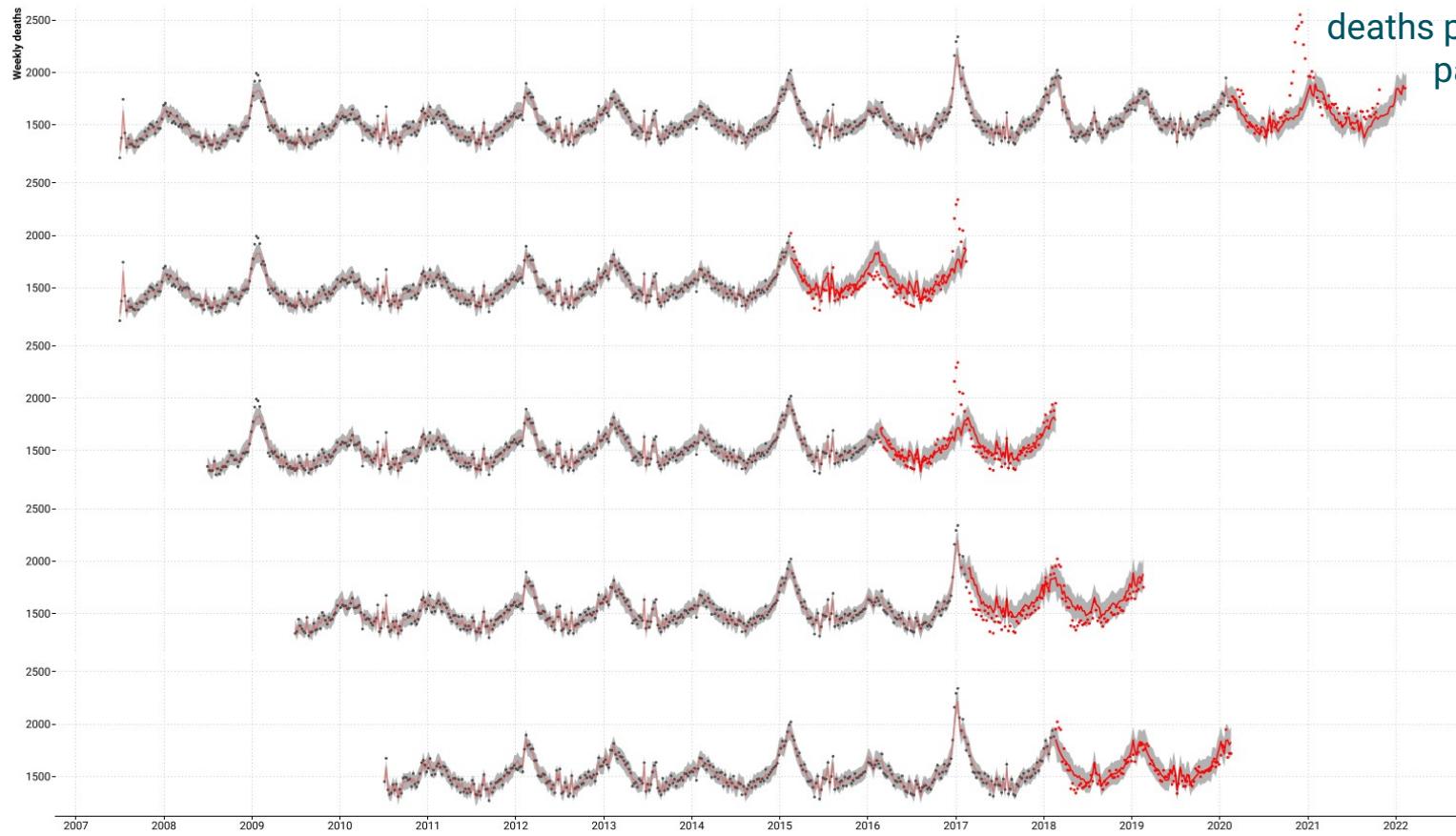
Cumulative weekly excess deaths Germany



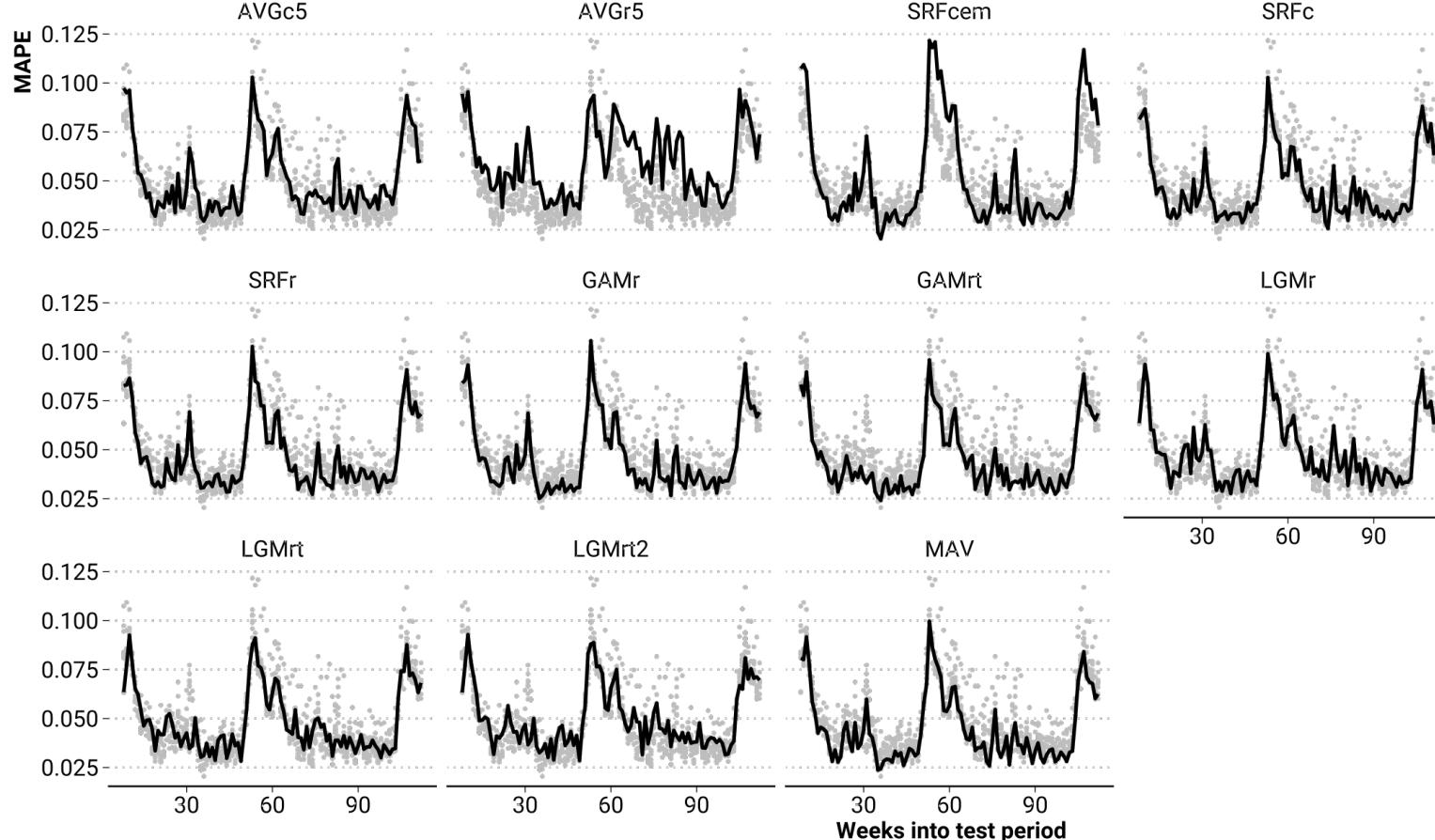
Cross-validate predictive accuracy & model calibration

Cross validate – Error & Bias

Rolling origin four-fold cross-validation setup
mirroring the task of predicting weekly
deaths past the beginning of the COVID-19
pandemic given pre-pandemic data.

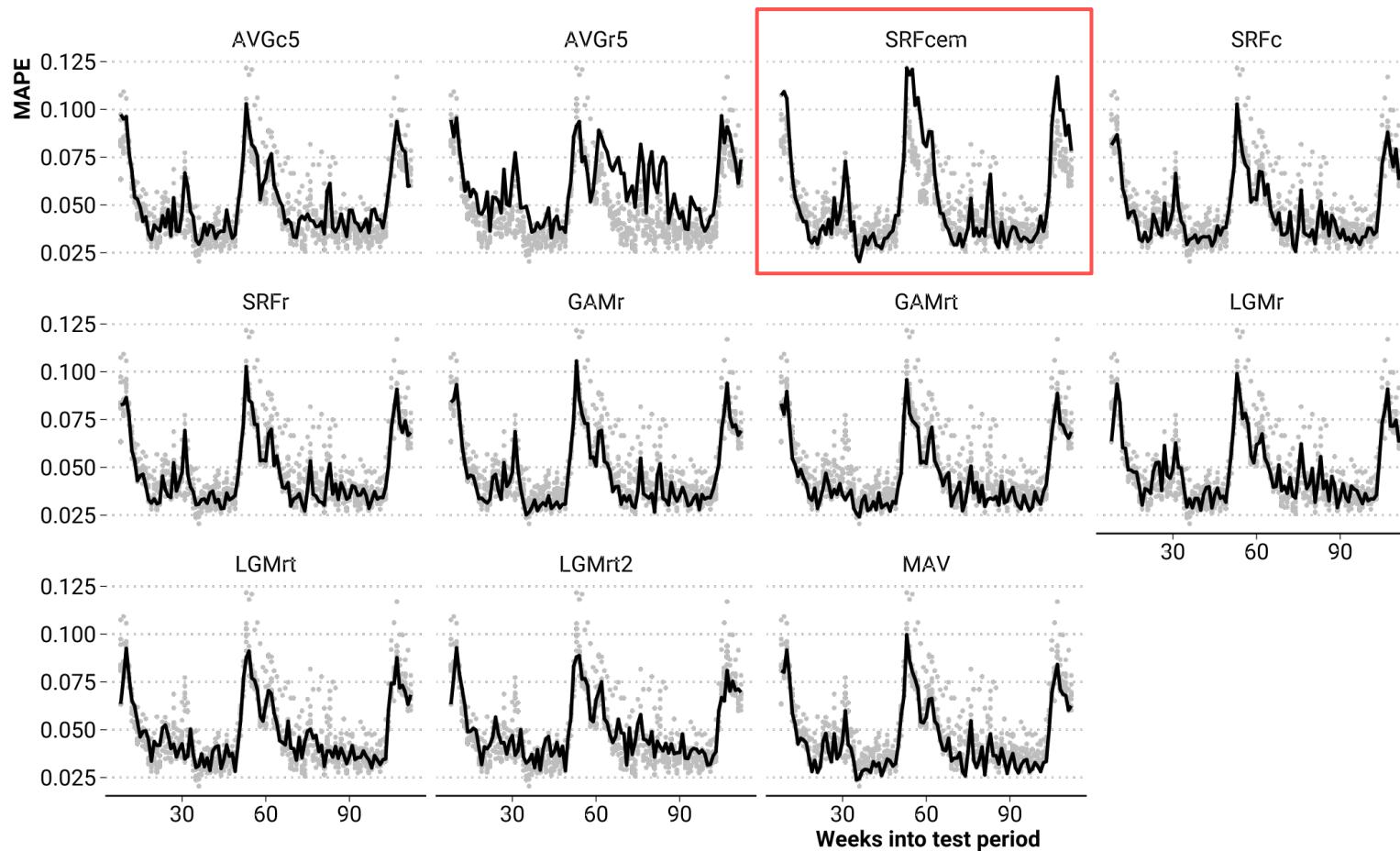


Cross validate – Error & Bias



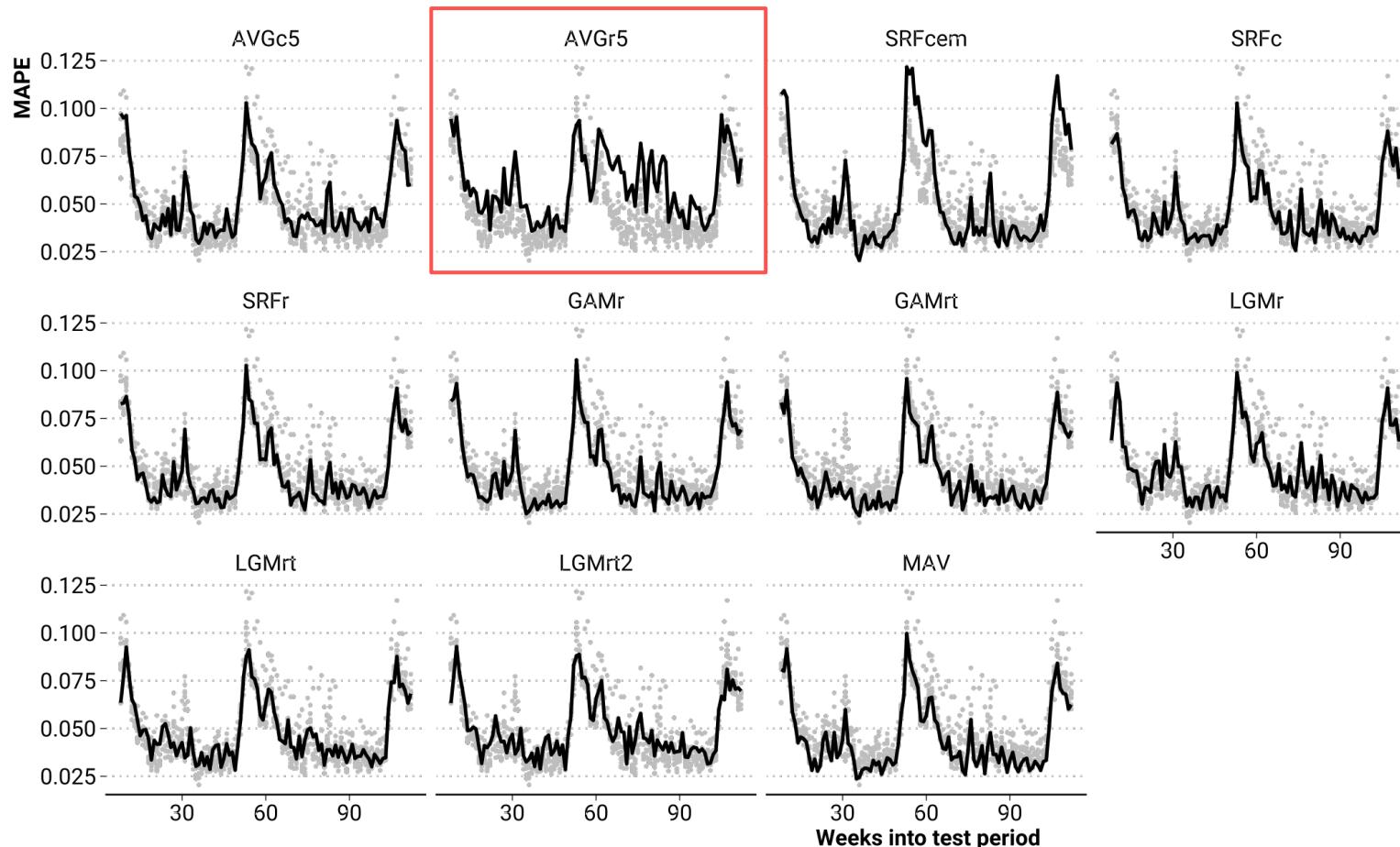
Mean absolute percentage error of weekly death counts for different models.
Grey points show MAPE of all other models

Cross validate – Error & Bias



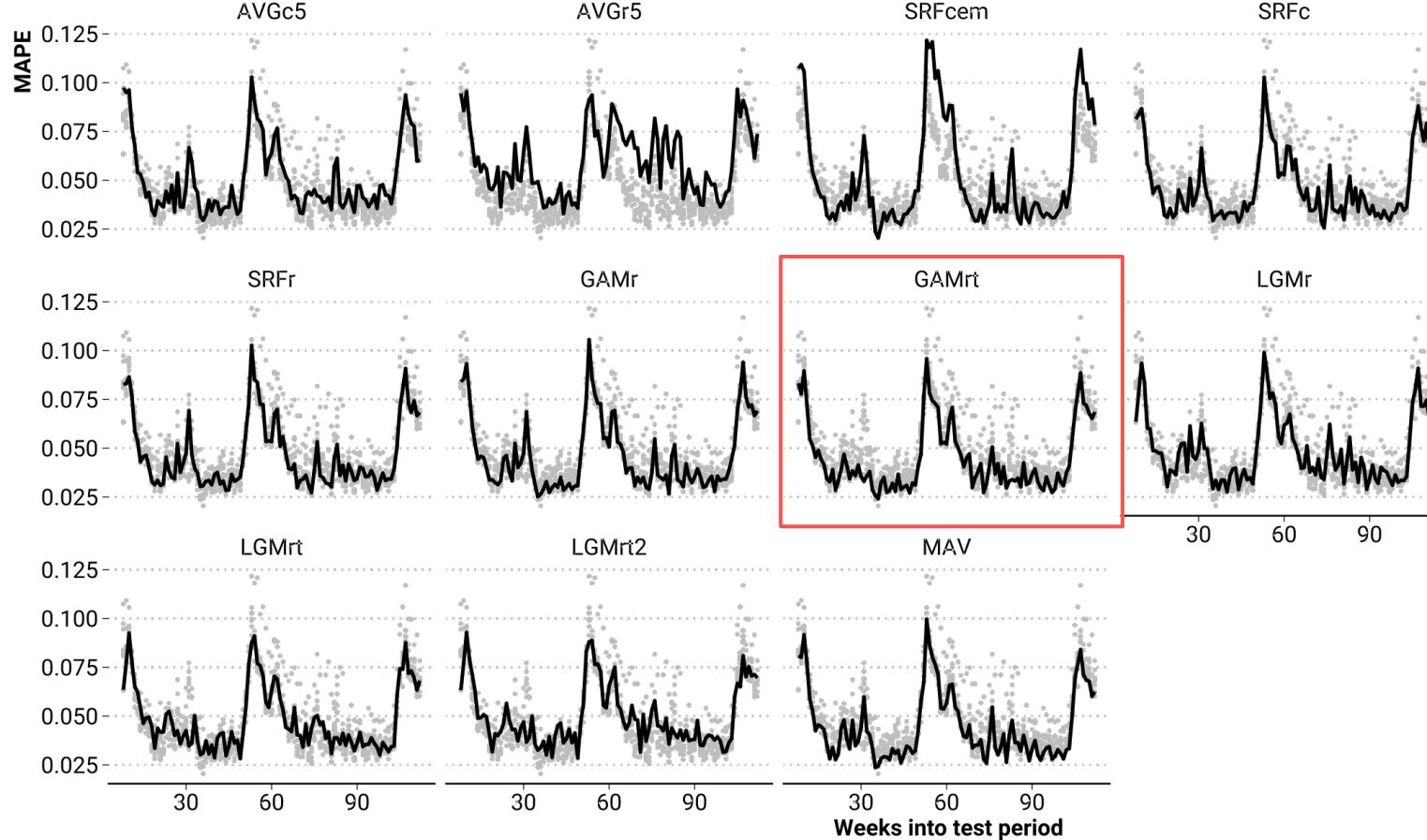
Mean absolute percentage error of weekly death counts for different models.
Grey points show MAPE of all other models

Cross validate – Error & Bias



Mean absolute percentage error of weekly death counts for different models.
Grey points show MAPE of all other models

Cross validate – Error & Bias

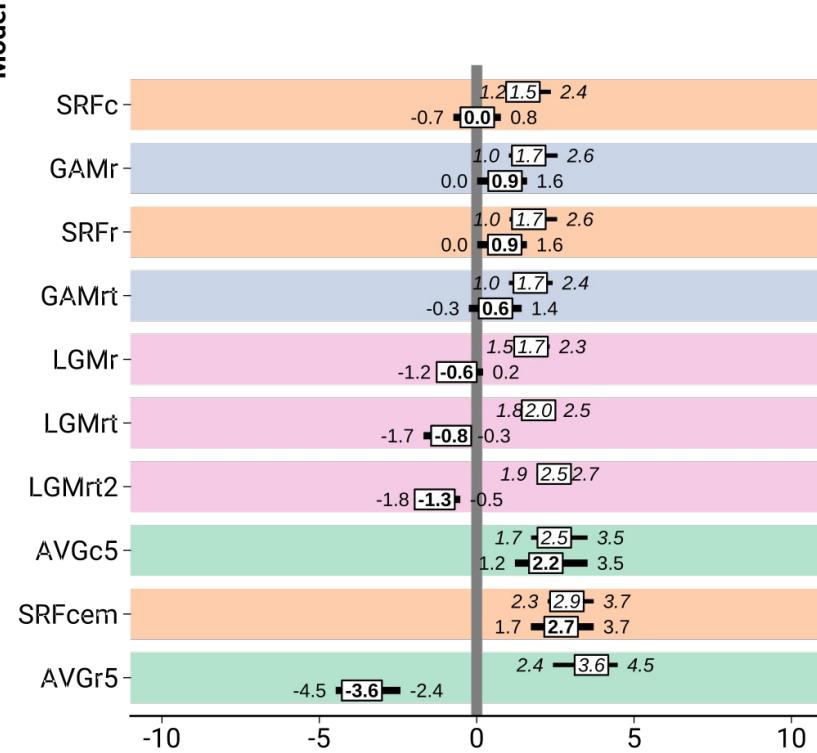


Mean absolute percentage error of weekly death counts for different models.
Grey points show MAPE of all other models

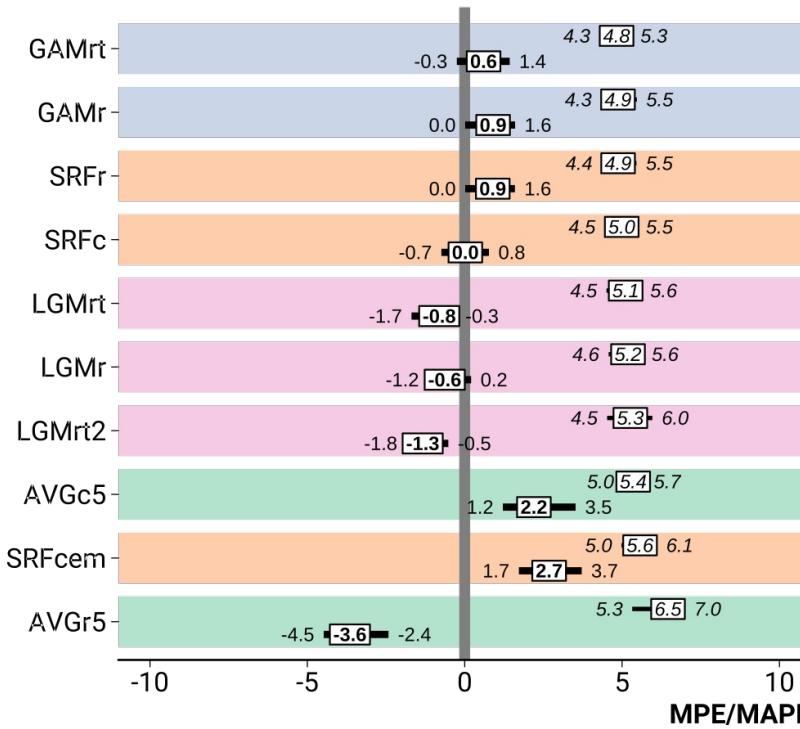
Cross validate – Error & Bias

Bias (MPE, bold) and error (MAPE, italic) by model when predicting death counts on test data.

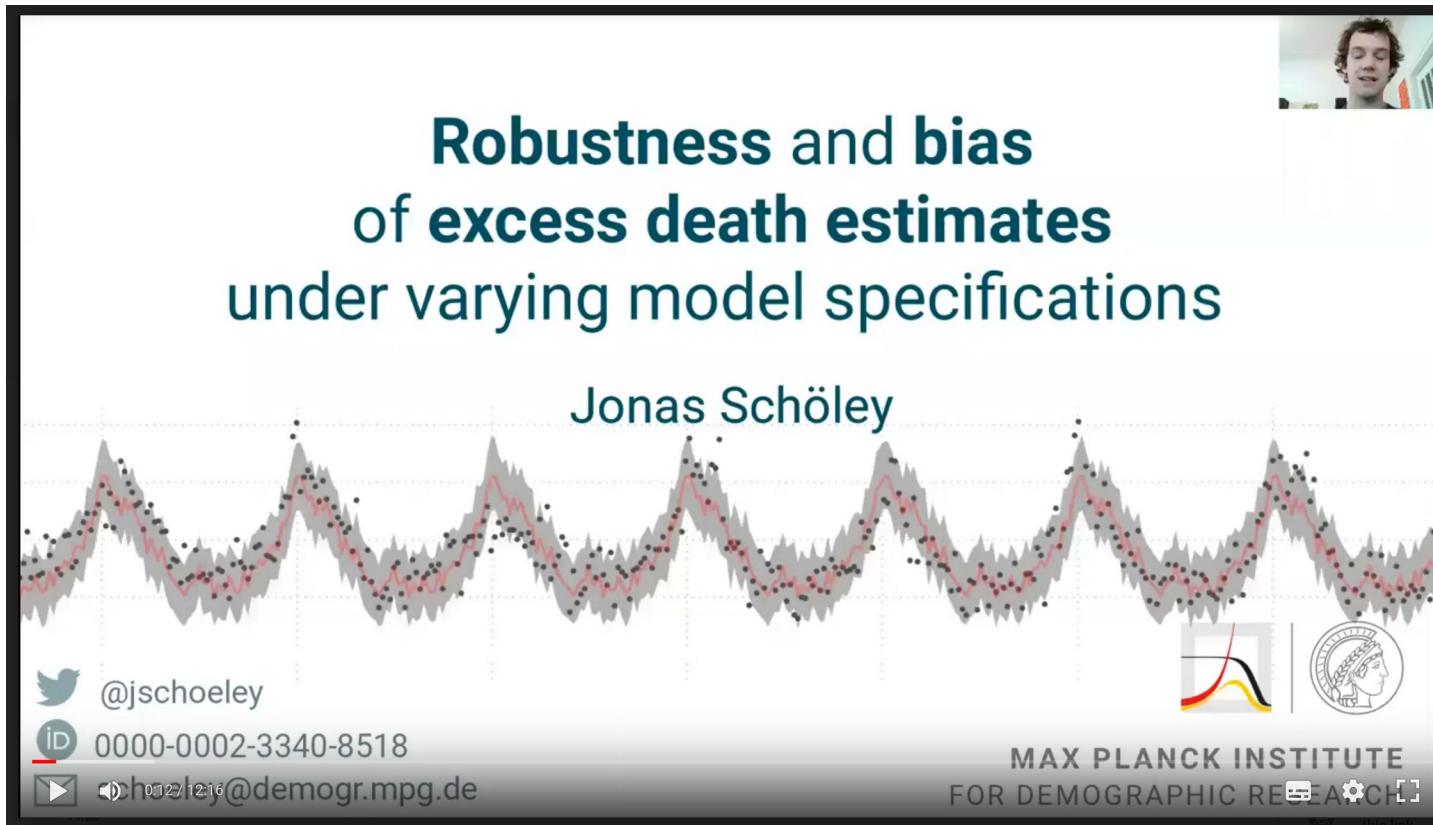
a. Total annual deaths by country



b. Total weekly deaths by country



Cross validation – Error & Bias



A video call interface showing a presentation slide. In the top right corner, there is a small video window of a man with curly hair. The main slide title is "Robustness and bias of excess death estimates under varying model specifications" in bold blue text. Below the title, the name "Jonas Schöley" is displayed in a larger, semi-transparent font. The slide features a background plot with black dots, a red line, and a grey shaded area. At the bottom left, there are social media icons and contact information: a Twitter icon with "@jschoeley", an ORCID icon with "0000-0002-3340-8518", and an email icon with "schoeley@demogr.mpg.de". At the bottom right, there is a logo for the MAX PLANCK INSTITUTE FOR DEMOGRAPHIC RESEARCH.

Robustness and bias
of excess death estimates
under varying model specifications

Jonas Schöley

@jschoeley

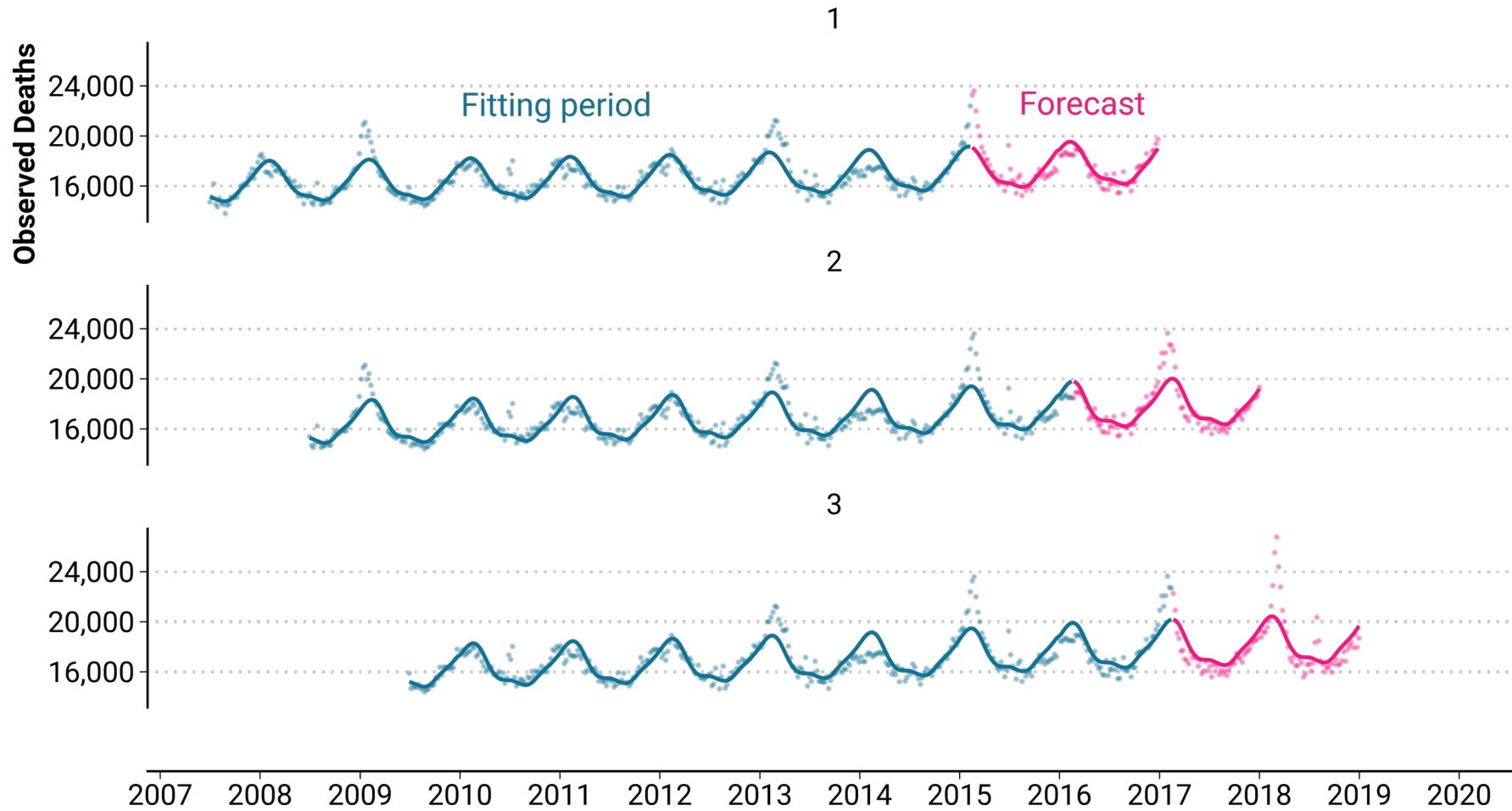
0000-0002-3340-8518

schoeley@demogr.mpg.de

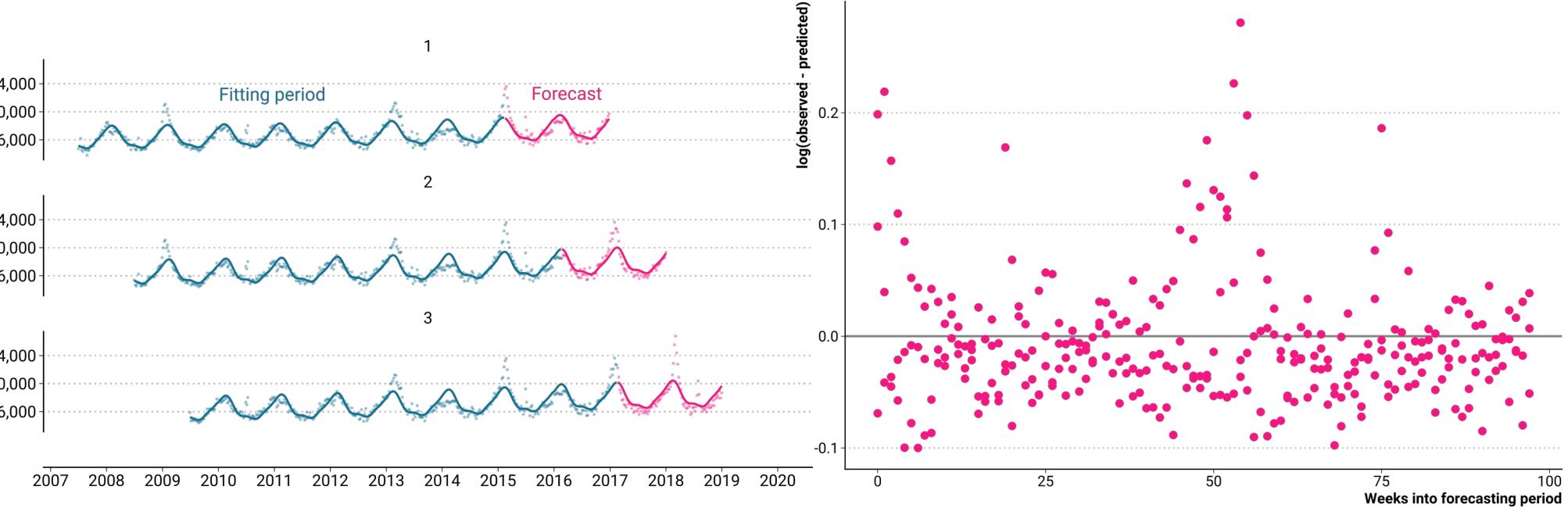
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Schöley (2021). Robustness and bias in excess death estimates. [Link to video](#)

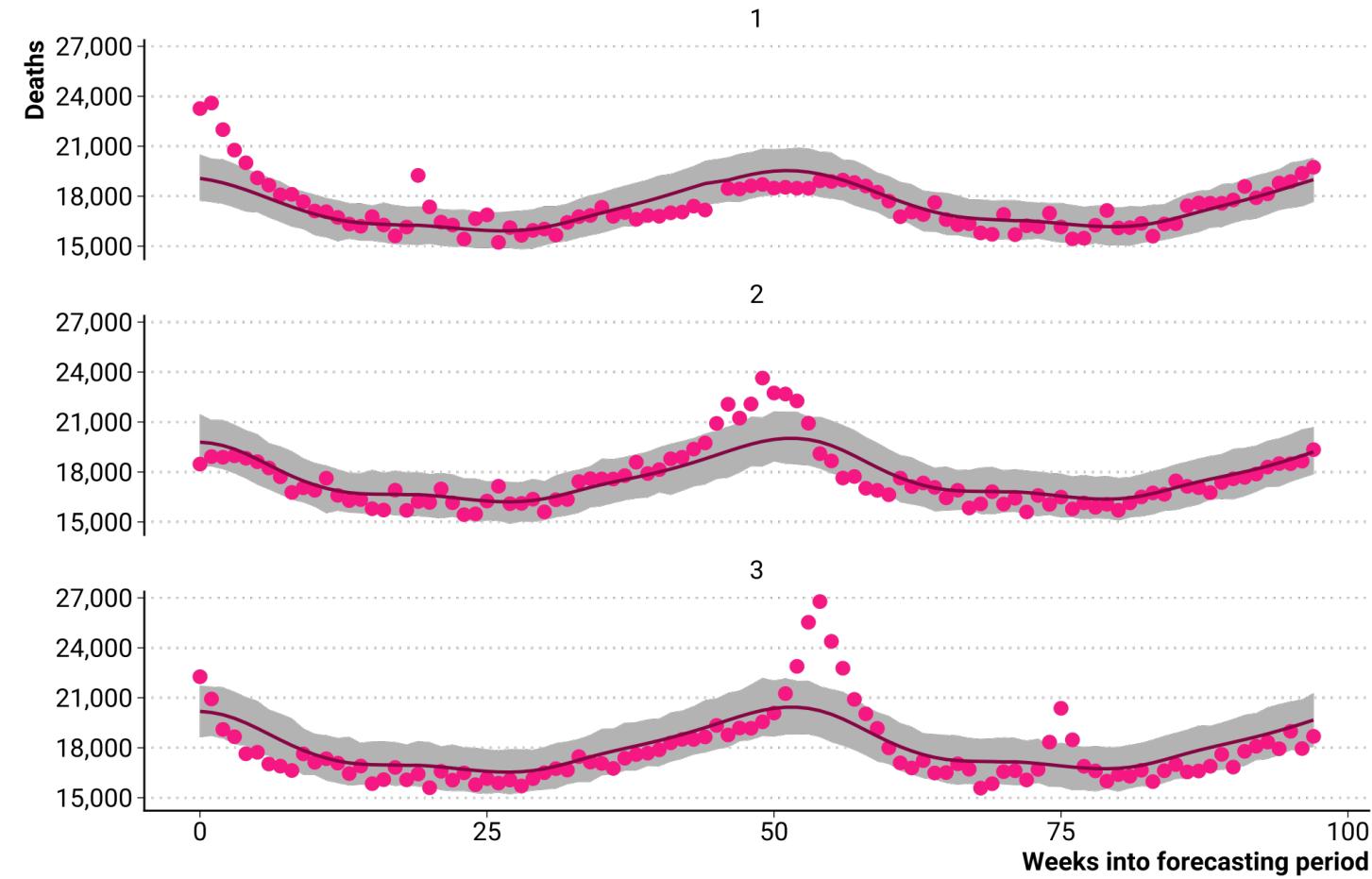
Cross validation – Calibration



Cross validation – Calibration

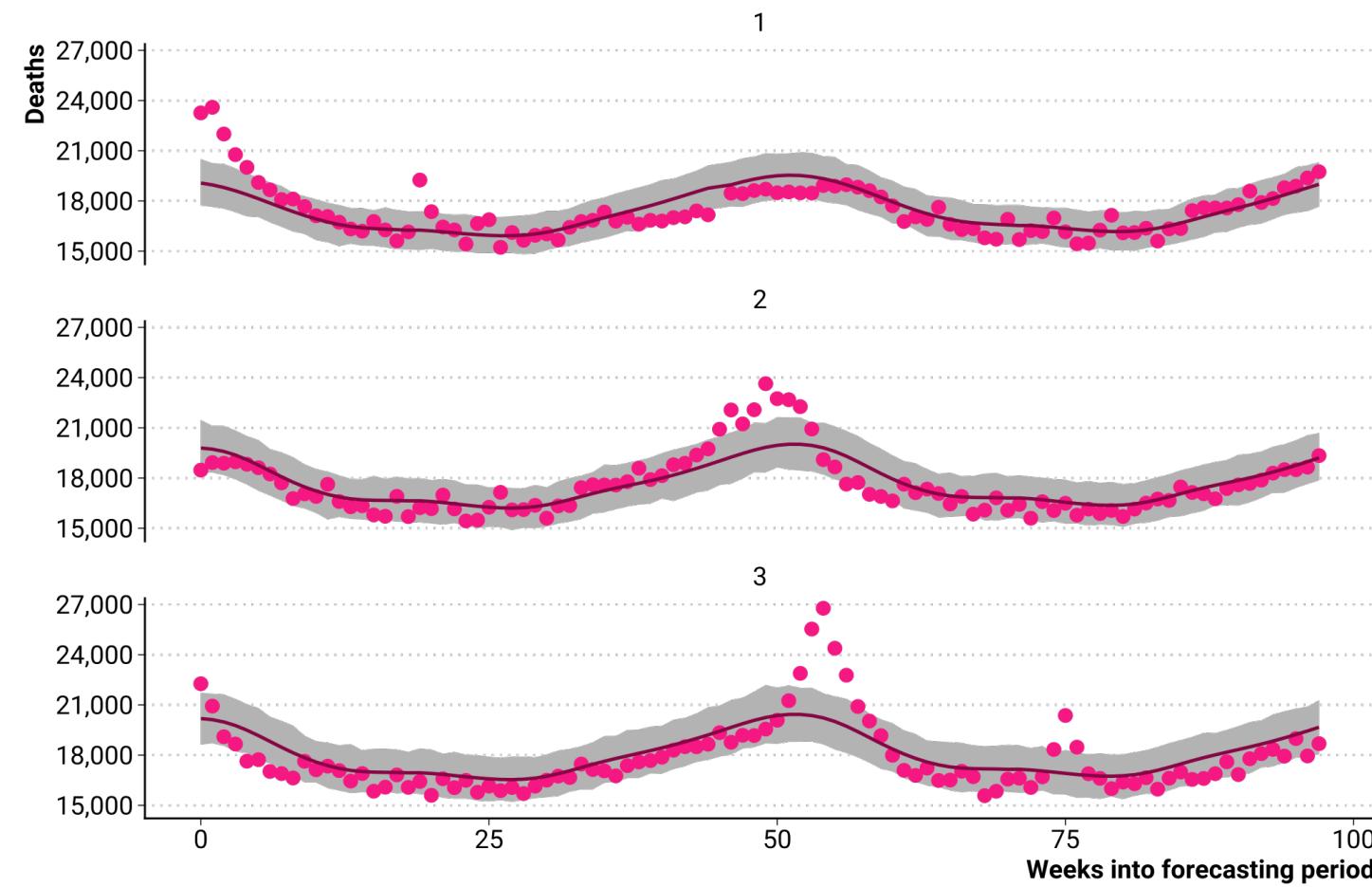


Cross validation – Calibration



Prediction interval with
90% nominal coverage
via Negative-Bin.
GAM model

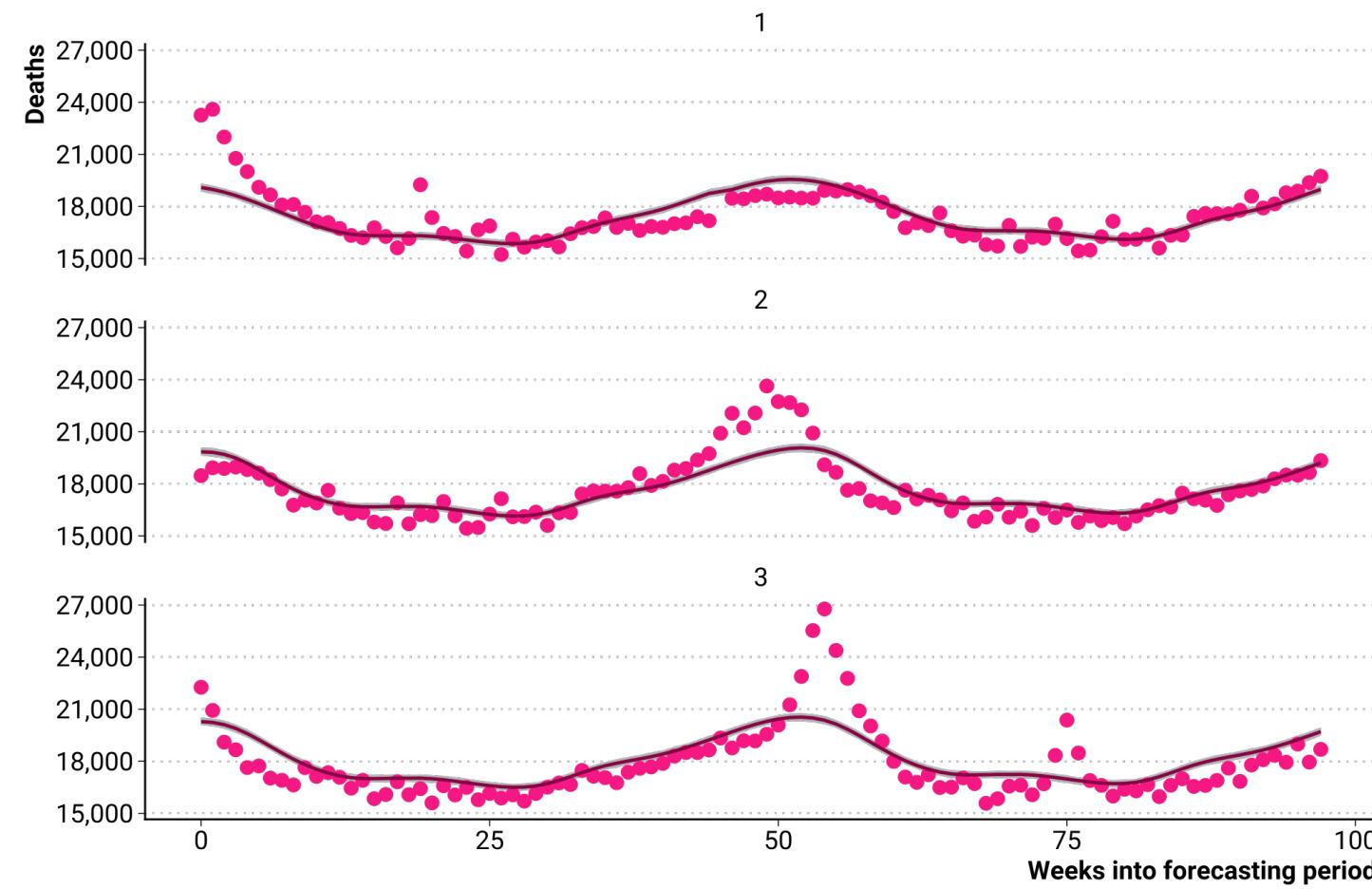
Cross validation – Calibration



Prediction interval with
90% nominal coverage
via Negative-Bin.
GAM model

Actual coverage ~87%

Cross validation – Calibration



Prediction interval with
90% nominal coverage
via Poisson GAM model

Actual coverage ~22%

Cross validation – Calibration

Empirical prediction intervals applied to short-term mortality forecasts and excess deaths



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Schöley (2022). Empirical prediction intervals. [Link to video](#)

Reproducible analysis

github.com/jschoeley/phds22-predictive_modeling

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