Excess deaths associated with covid-19 pandemic in 2020: age and sex disaggregated time series analysis in 29 high income countries

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Glossary

Observed deaths: Deaths reported by the individual countries.

Expected deaths: Deaths that would be expected in 2020 based on historical data (2016-2019), separately calculated by country, calendar year, week of the year, age, and sex. These numbers are calculated from our model after taking into account the recent temporal trend and seasonal variation in mortality.

Excess deaths: Observed minus expected deaths.

Avoided mortality: When the observed deaths are below the expected deaths. Also known as "mortality deficit".

Mortality displacement: When a period of excess deaths is followed by a mortality deficit. This indicates that people who have died would have died even in the absence of the event (Covid-19 pandemic, in this case), but their death was brought forward by the event.

Supplementary Methods

Statistical model:

Denote $Y_{s,c,a}(t)$ as the number of deaths at week t for individuals of sex s, in country c, and age group a. Assume that $Y_{s,c,a}(t) \sim Poisson\left(\mu_{s,c,a}(t)\right)$, then our mean model is:

$$\mu_{s,c,a}(t) = N_{s,c,a}(t)exp\{\beta t \; + \; g_{s,c,a}(w_t)\} \text{ for } t \in I_c \tag{1}$$

The expected number of deaths at week t for individuals of sex s, in country c, and age group a is represented with $\mu_{s,c,a}(t)$, $N_{s,c,a}(t)$ is an offset that accounts for the population size, β represents a linear effect of time that accounts for slow-moving changes in mortality, $g_{s,c,a}(w_t)$ is a function that accounts for seasonal trends, where $w_t \in \{1, \dots, 52\}$ represents a week of the year, and I_c is a country-specific training interval that is used to fit the model (Supplemental Table S2). For the function $g_{s,c,a}(t)$, we use a Fourier transform with two harmonics:

$$g_{s,c,a}(w_t) = \sum_{k=1}^{2} A_{s,c,a,k} \; \times \cos\left(\frac{2\pi k w_t}{52}\right) + \; B_{s,c,a,k} \; \times \sin\left(\frac{2\pi k w_t}{52}\right) \tag{2}$$

, where the $\boldsymbol{A} = [A_{s,c,a,1}, A_{s,c,a,2}]$ and $\boldsymbol{B} = [B_{s,c,a,1}, B_{s,c,a,2}]$ parameters are estimated from data. We fit model (1) via Maximum Likelihood and estimated the counterfactual death counts in 2020 for each sex-age group in each country.

Now, we turn the focus to obtaining smooth estimates of percent change from average. Let t' be a week in 2020, then:

$$\lambda_{s,c,a}(t') = \hat{\mu}_{s,c,a}(t')exp\{f_{s,c,a}(t')\} \tag{3}$$

In model (3), $\lambda_{s,c,a}(t')$ represents the average number of observed deaths at week t' for individuals of sex s, in country c, and age group a. The number of deaths at week t' in the counterfactual scenario of no pandemic is represented with $\hat{\mu}_{s,c,a}(t')$ and it is used as an offset. Lastly, the function $f_{s,c,a}(t')$ is a natural cubic spline with 12 internal knots. It follows that $\hat{\gamma}_{s,c,a}(t') = \; \hat{\lambda}_{s,c,a}(t')/\; \hat{\mu}_{s,c,a}(t') - 1$ represents a smooth estimate of percent change from average at t'. Using a first-order Taylor approximation and the assumptions from above we have that:

$$Var\left(\hat{\gamma}_{s,c,a}(t')\right) \approx \frac{\hat{\lambda}^2{}_{s,c,a}(t')}{\hat{\mu}^2{}_{s,c,a}(t')}\left(Var\left(\log \hat{\lambda}_{s,c,a}(t')\;\right) + \hat{\mu}^{-2}{}_{s,c,a}(t')Var\left(\log \hat{\mu}_{s,c,a}(t')\;\right)\right) \tag{4}$$

Furthermore, we computed excess deaths at t' with:

$$\widehat{\Delta}_{s,c,a}(t') = Y_{s,c,a}(t') - \hat{\mu}_{s,c,a}(t') \tag{5}$$

Using a first-order Taylor approximation and the assumptions from above we have that:

$$Var\left(\widehat{\Delta}_{s,c,a}(t')\right) \approx \left(\hat{\phi}_{s,c,a}\hat{\lambda}_{s,c,a}(t') + \hat{\mu}_{s,c,a}(t')Var\left(\log \hat{\mu}_{s,c,a}(t')\right)\right) \tag{6}$$

, where $\hat{\phi}_{s,c,a}$ is the estimated dispersion parameter from model (3).

Finally, to get marginal effects for males and females in each country, we took a weighted average of the age-specific estimates. Specifically, the percent change from average for individuals of sex s in country c is:

$$\hat{\gamma}_{s,c}(t') = \frac{\sum_{a \in Age\ groups} \hat{\mu}_{s,c,a}(t') \times \hat{\gamma}_{s,c,a}(t')}{\sum_{a \in Age\ groups} \hat{\mu}_{s,c,a}(t')} = \sum_{a \in Age\ groups} \hat{\pi}_{s,c,a}(t') \times \hat{\gamma}_{s,c,a}(t') \tag{7}$$

, where $\hat{\pi}_{s,c,a}(t') = 1 \,/\, \sum_{a \in Age\ groups} \hat{\mu}_{s,c,a}(t')$. Note that we can obtain variability estimates for $\hat{\gamma}_{s,c}(t')$ in equation (3) using a first-order Taylor approximation.

Discrepancies between the reported Covid-19 deaths and the estimated excess deaths:

Many countries reported their official statistics on Covid-19 deaths. Previous research highlighted that there could be under-reporting of Covid-19 due to a host of reasons including a difference in the definition of Covid-19 deaths, inadequate testing facility to precisely diagnose the cause of death, some degrees of diagnostic inaccuracy in the diagnostic tests used to detect the SARS-CoV-2 virus, delay in reporting etc. Therefore, when we see that the reported number of Covid-19 deaths is lower than the estimated excess deaths, it is understood more intuitively. However, a higher excess death does not necessarily mean that there was an under-reporting or underestimation of the Covid-19 deaths. It could also be due to an increase in mortality due to causes other than Covid-19 (for example, more deaths due to delayed medical care, suicide, domestic violence etc. potentially associated with the disruption of healthcare services due to prolonged lockdown). In reality the difference is more likely due to a mix of these factors.

In contrast, it is less intuitive to understand why Covid-19 death counts could be higher than the estimated excess deaths. For example, if we conclude that the estimated number of excess deaths in a specific country was 1,000, but the country already has reported, let's say, 1,500 deaths due to Covid-19. So, how is it possible that the excess death is lower than the reported Covid-19 deaths? Aren't all deaths due to Covid-19 already part of the 'excess' deaths? The answer lies in the estimation process.

Death and death rates are always non-negative (zero or more). However, because 'excess death' is defined as a difference between the observed and the expected number of deaths (observed minus expected, to be precise), it can be (and indeed was) negative in many countries (when the observed death was lower than the expected death), especially in specific subgroups (mostly in younger age groups). When we add negative numbers, the total would be lower than the sum of all the positive numbers. For example, if we have 300 excess deaths each in the four older age groups, we already have 4*300= 1,200 excess deaths. But if there were 200 fewer deaths in the youngest age groups, then altogether we will have 1,000 deaths (1,200 – 200 = 1,000), which is lower than the total of the other four age groups!

Lastly, overall excess death is a combination of Covid-19 and non-Covid deaths. For example, let's say, we have 1,500 deaths from Covid-19, but 500 fewer deaths than expected for other non-Covid deaths (maybe due to lower road traffic accidents, or lower occupational hazards, or lower levels of pollution potentially associated with lockdown measures). The overall excess deaths would be 1,000 (1,500 – 500 = 1,000), which is lower than the reported Covid-19 deaths.

Population estimates

For each stratum, we assumed a constant rate of change in the population size between the mid-year estimates. Hence, from week 26, 2016, to week 26, 2020, we calculated population sizes via linear interpolation of the mid-year population estimates. For the first six months of 2016, we assumed the same rate of change as in mid-2016 to mid-2017, thus we extrapolated the population back in time using a linear model. Similarly, for the last six months of 2020, we assumed the same rate of change as in mid-2019 to mid-2020 and extrapolated using a linear model.

Crude and age-standardised <u>annual</u> mortality rates

We examined the annual mortality rate (per 100,000 population) in each of the aggregate age groups and for all ages, separately in men and women. To address the differential demographic structure across all the countries included in our analysis, we used age-standardised mortality rate (per 100,000 population) calculated by the direct method of agestandardisation with the 2013 European Standard Population.[1] Since the death counts, especially in the youngest age groups (<15 years) could be very low in some countries, we applied the methods proposed by Fay and Feuer (modified by Tiwari et al.) to calculate the confidence intervals for age-standardised rates between 2016 and 2020, separately in men and women.[2,3]

Table S1: Sources of the Short-Term Mortality Fluctuation data for 29 high-income countries

Country code	Country name	Data source
AUT	Austria	Statistik Austria
BEL	Belgium	STATBEL and Eurostat
CHE	Switzerland	Eurostat and Swiss Federal Statistical Office
CZE	Czech Republic	Statistical Office and Eurostat
DEU	Germany	Statistisches Bundesamt
DNK	Denmark	Statistics Denmark
ESP	Spain	National Statistical Office
EST	Estonia	Eurostat
FIN	Finland	Statistics Finland
FRA	France	INSERM
ENW	England and Wales	Office for National Statistics
NIR	Northern Ireland	Eurostat
SCO	Scotland	National Statistical Office
GRC	Greece	Eurostat
HUN	Hungary	Eurostat
ISR	Israel	Stat Office
ITA	Italy	ISTAT
KOR	South Korea	Statistics Korea
LTU	Lithuania	Statistics Lithuania
LVA	Latvia	Eurostat
NLD	Netherlands	Statistics Netherlands
NOR	Norway	Statistics Norway
NZL	New Zealand	Statistics New Zealand
POL	Poland	Eurostat
PRT	Portugal	Direção-Geral da Saúde (General Directorate of Health)
SVK	Slovakia	Eurostat
SVN	Slovenia	Eurostat
SWE	Sweden	Statistics Sweden
USA	USA	Centers for Disease Control and Prevention

For details please see https://www.mortality.org/Public/STMF_DOC/STMFNote.pdf. The data was further harmonised for the purpose of this analysis (described in the main paper).

Table S2: Dates excluded from the counterfactual estimation for 2020 in 29 high-income countries

Country	Excluded dates
Austria, Belgium, Czech Republic, England & Wales, Estonia, Finland, Germany, Northern Ireland, Slovakia, Norway, Poland, Sweden, Switzerland, and Netherlands	2016-12-01 to 2017-04-30, & 2017-12-01 to 2018-04-30
Greece, Portugal	2016-12-01 to 2017-04-30, & 2018-12-01 to 2019-04-30
Hungary, Lithuania, Slovenia, Spain	2016-12-01 to 2017-04-30, 2017-12-01 to 2018-04-30, & 2018-12-01 to 2019-04-30
Denmark, Latvia, United States, Scotland, South Korea	2017-12-01 to 2018-04-30
France, Israel, Italy	2016-12-01 to 2017-04-30
New Zealand	2017-06-01 to 2017-08-31

Table S3: Estimated number (95% confidence interval) of excess deaths by age and sex in 2020 in 29 high-income countries

	Estimated number of excess deaths in 2020 (95% confidence interval)									
	0 to 14 years		15 to 64 years		65 to 74 years		75 to 84 years		85 or above years	
Country	Female	Male	Female	Male	Female	Male	Female	Male	Female	Male
Austria	0 (-20 to 30)	-10 (-30 to 20)	170 (40 to 290)	570 (400 to 740)	140 (0 to 280)	650 (480 to 830)	1,300 (1,100 to 1,500)	1,600 (1,400 to 1,800)	1,300 (1,100 to 1,600)	1,000 (790 to 1,200)
Belgium	-90 (-120 to -50)	-140 (-180 to -110)	250 (100 to 400)	1,200 (1,000 to 1,400)	530 (360 to 690)	1,600 (1,400 to 1,800)	2,600 (2,400 to 2,800)	3,100 (2,900 to 3,300)	5,500 (5,200 to 5,900)	3,200 (3,000 to 3,500)
Czech Republic	-30 (-60 to -10)	-10 (-40 to 20)	270 (120 to 420)	760 (540 to 980)	960 (760 to 1,200)	2,200 (1,900 to 2,400)	2,500 (2,200 to 2,700)	3,200 (3,000 to 3,500)	2,700 (2,400 to 3,000)	1,800 (1,600 to 2,000)
Denmark	0 (-20 to 20)	20 (-10 to 40)	100 (0 to 200)	-100 (-240 to 30)	-40 (-170 to 80)	-100 (-250 to 60)	50 (-120 to 220)	-30 (-210 to 160)	-220 (-440 to -10)	170 (0 to 340)
England & Wales	-130 (-200 to -50)	-90 (-180 to -10)	3,600 (3,300 to 4,000)	6,600 (6,200 to 7,000)	4,400 (4,000 to 4,800)	8,000 (7,600 to 8,500)	11,400 (10,900 to 12,000)	15,500 (15,000 to 16,100)	21,100 (20,400 to 21,700)	14,900 (14,300 to 15,400)
Estonia	0 (-10 to 10)	-10 (-20 to 0)	140 (90 to 190)	270 (180 to 360)	10 (-50 to 80)	-40 (-130 to 40)	20 (-80 to 120)	60 (-20 to 150)	170 (50 to 290)	40 (-30 to 110)
Finland	-20 (-40 to 0)	-10 (-30 to 10)	-40 (-130 to 60)	380 (250 to 520)	170 (50 to 290)	80 (-70 to 240)	20 (-140 to 180)	200 (30 to 380)	190 (-40 to 420)	30 (-140 to 200)
France	-120 (-200 to -50)	-270 (-360 to -180)	180 (-170 to 530)	2,000 (1,500 to 2,500)	1,600 (1,300 to 2,000)	4,600 (4,100 to 5,100)	4,800 (4,300 to 5,200)	8,400 (7,800 to 8,900)	12,500 (11,600 to 13,300)	9,900 (9,300 to 10,500)
Germany	90 (20 to 170)	40 (-40 to 120)	340 (-80 to 760)	3,600 (3,000 to 4,100)	590 (140 to 1,000)	2,700 (2,200 to 3,300)	3,200 (2,400 to 3,900)	5,700 (4,900 to 6,500)	4,000 (3,100 to 5,000)	5,600 (4,900 to 6,300)
Greece	-40 (-70 to -10)	30 (0 to 60)	480 (340 to 610)	270 (70 to 470)	480 (330 to 640)	610 (400 to 820)	1,800 (1,500 to 2,000)	1,200 (890 to 1,400)	1,400 (1,100 to 1,800)	1,500 (1,200 to 1,800)
Hungary	-10 (-40 to 20)	-10 (-40 to 30)	820 (640 to 1,000)	1,500 (1,300 to 1,800)	1,900 (1,700 to 2,100)	2,500 (2,300 to 2,800)	3,100 (2,800 to 3,400)	2,600 (2,300 to 2,800)	2,700 (2,400 to 3,000)	1,400 (1,200 to 1,600)
Israel	-50 (-80 to -10)	-90 (-130 to -40)	60 (-40 to 160)	120 (-10 to 260)	20 (-100 to 130)	480 (350 to 620)	180 (30 to 330)	420 (270 to 580)	480 (280 to 690)	380 (210 to 550)
Italy	-40 (-100 to 10)	-70 (-130 to -10)	1,400 (1,100 to 1,700)	4,400 (4,000 to 4,800)	4,200 (3,900 to 4,600)	11,300 (10,800 to 11,700)	11,800 (11,200 to 12,300)	18,700 (18,100 to 19,300)	22,800 (21,900 to 23,700)	14,600 (14,000 to 15,300)
Latvia	10 (-10 to 20)	10 (0 to 30)	-30 (-120 to 50)	-90 (-210 to 40)	30 (-60 to 120)	160 (50 to 270)	340 (210 to 480)	20 (-100 to 140)	200 (50 to 350)	160 (70 to 240)
Lithuania	-10 (-20 to 10)	10 (-10 to 30)	350 (250 to 440)	1,200 (1,000 to 1,300)	370 (270 to 470)	970 (850 to 1,100)	1,200 (1,000 to 1,300)	1,100 (930 to 1,200)	1,300 (1,100 to 1,400)	480 (370 to 590)
Netherlands	20 (-20 to 50)	0 (-40 to 40)	210 (30 to 390)	730 (520 to 940)	670 (460 to 880)	1,700 (1,500 to 2,000)	1,900 (1,600 to 2,100)	3,600 (3,300 to 3,900)	3,800 (3,400 to 4,200)	2,700 (2,400 to 3,000)
New Zealand	-40 (-70 to -20)	-50 (-70 to -20)	-70 (-170 to 30)	-330 (-450 to -200)	-230 (-330 to -130)	-200 (-320 to -80)	-160 (-290 to -40)	-290 (-430 to -150)	-760 (-930 to -590)	-380 (-520 to -230)
Northern Ireland	-10 (-30 to 0)	-20 (-40 to 0)	70 (0 to 130)	170 (90 to 250)	230 (170 to 290)	260 (190 to 330)	330 (240 to 420)	400 (310 to 500)	540 (430 to 650)	220 (130 to 310)
Norway	-10 (-20 to 10)	-30 (-50 to 0)	30 (-60 to 110)	0 (-110 to 110)	-10 (-120 to 90)	150 (20 to 270)	-180 (-320 to -40)	-50 (-200 to 100)	-10 (-210 to 190)	20 (-140 to 180)
Poland	-140 (-200 to -80)	-30 (-90 to 30)	860 (540 to 1,200)	4,500 (4,000 to 5,000)	4,800 (4,400 to 5,200)	10,900 (10,400 to 11,400)	6,100 (5,600 to 6,500)	10,000 (9,500 to 10,400)	13,100 (12,600 to 13,700)	10,000 (9,600 to 10,400)
Portugal	-20 (-50 to 10)	-40 (-70 to -10)	260 (120 to 390)	740 (530 to 940)	600 (450 to 740)	710 (510 to 910)	1,700 (1,500 to 1,900)	1,500 (1,200 to 1,700)	2,000 (1,600 to 2,300)	1,100 (830 to 1,400)
Scotland	0 (-20 to 20)	-10 (-40 to 10)	120 (0 to 250)	870 (720 to 1,000)	400 (270 to 530)	870 (730 to 1,000)	890 (710 to 1,100)	1,100 (950 to 1,300)	1,500 (1,300 to 1,700)	1,000 (870 to 1,200)
Slovakia	-20 (-40 to 10)	-10 (-40 to 20)	60 (-60 to 180)	130 (-50 to 310)	440 (300 to 580)	650 (470 to 820)	900 (720 to 1,100)	1,100 (930 to 1,200)	710 (520 to 900)	480 (350 to 600)
Slovenia	0 (-10 to 10)	0 (-10 to 10)	30 (-30 to 90)	210 (120 to 300)	40 (-30 to 110)	130 (30 to 230)	530 (430 to 630)	490 (380 to 600)	1,000 (900 to 1,200)	760 (670 to 850)
South Korea	-120 (-170 to -70)	-130 (-190 to -80)	730 (460 to 990)	-650 (-1,100 to -230)	130 (-100 to 370)	800 (440 to 1,100)	1,200 (810 to 1,600)	1,300 (860 to 1,800)	220 (-270 to 710)	480 (140 to 820)
Spain	20 (-30 to 70)	60 (10 to 120)	1,800 (1,500 to 2,000)	3,100 (2,700 to 3,500)	3,400 (3,100 to 3,600)	6,800 (6,400 to 7,200)	11,200 (10,800 to 11,600)	14,200 (13,700 to 14,600)	26,600 (26,000 to 27,300)	17,000 (16,500 to 17,500)
Sweden	10 (-10 to 40)	50 (30 to 80)	70 (-50 to 180)	490 (350 to 630)	280 (130 to 420)	640 (470 to 820)	1,300 (1,100 to 1,500)	1,900 (1,700 to 2,200)	2,400 (2,100 to 2,700)	2,000 (1,800 to 2,300)
Switzerland	10 (-20 to 40)	30 (0 to 60)	10 (-100 to 120)	260 (130 to 400)	50 (-70 to 170)	290 (140 to 440)	570 (390 to 740)	1,300 (1,100 to 1,400)	2,200 (1,900 to 2,500)	2,200 (2,000 to 2,400)
United States	-360 (-580 to -140)	-750 (-1,000 to -500)	39,500 (38,500 to 40,500)	91,500 (90,200 to 92,800)	37,200 (36,200 to 38,100)	57,100 (55,900 to 58,200)	52,700 (51,600 to 53,900)	56,700 (55,500 to 57,900)	83,500 (82,100 to 85,000)	40,500 (39,400 to 41,700)

Table S4: Median absolute difference of the excess mortality model (2016-2019)

	Median absolute difference	
Country	Female	Male
Austria	0.056	0.055
Belgium	0.060	0.049
Switzerland	0.065	0.062
Czech Republic	0.050	0.054
Germany	0.029	0.031
Denmark	0.059	0.064
England & Wales	0.038	0.041
Spain	0.041	0.035
Estonia	0.123	0.109
Finland	0.066	0.073
France	0.036	0.029
Greece	0.069	0.059
Hungary	0.055	0.062
Israel	0.064	0.049
Italy	0.045	0.042
South Korea	0.038	0.034
Lithuania	0.090	0.086
Latvia	0.075	0.081
Northern Ireland	0.112	0.119
Netherlands	0.050	0.041
Norway	0.074	0.068
New Zealand	0.061	0.053
Poland	0.038	0.040
Portugal	0.068	0.060
Scotland	0.067	0.062
Slovakia	0.078	0.068
Slovenia	0.109	0.106
Sweden	0.056	0.061
United States	0.013	0.013

Figure S1: Monthly excess death rates (per 100,000) by age and sex in 2020 in 29 high-income countries

Fig. S1 (A): <15 years

Note: empty (zero length) bars indicate no excess deaths in those months.

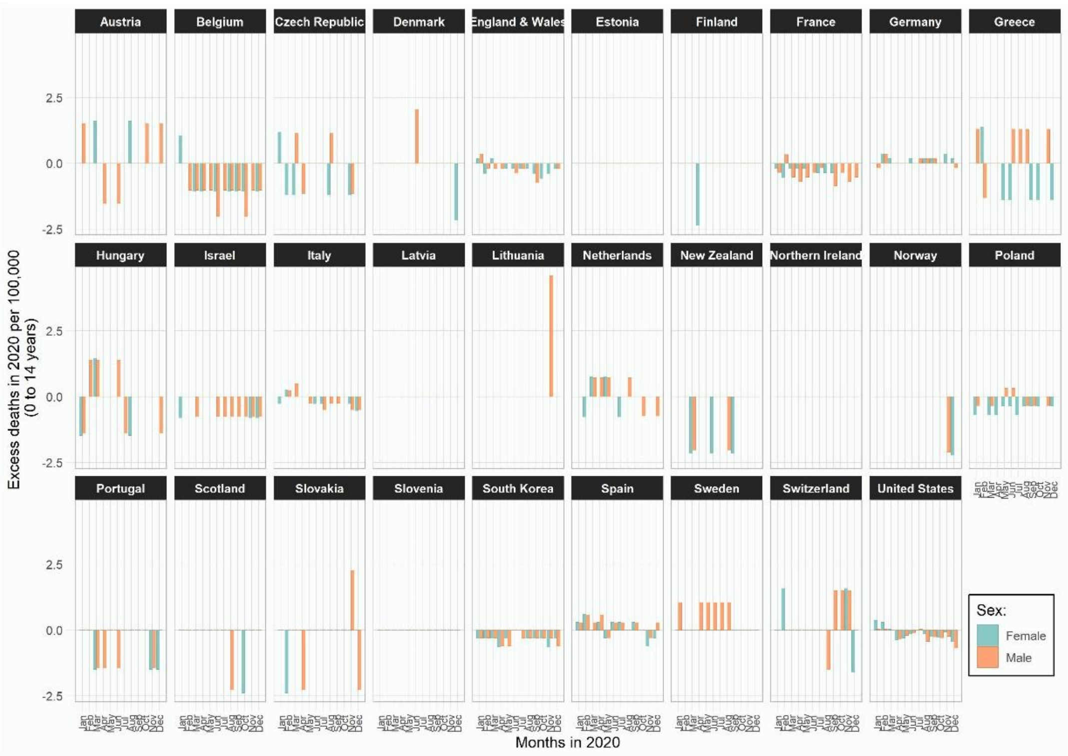


Fig. S1 (B): 15-64 years

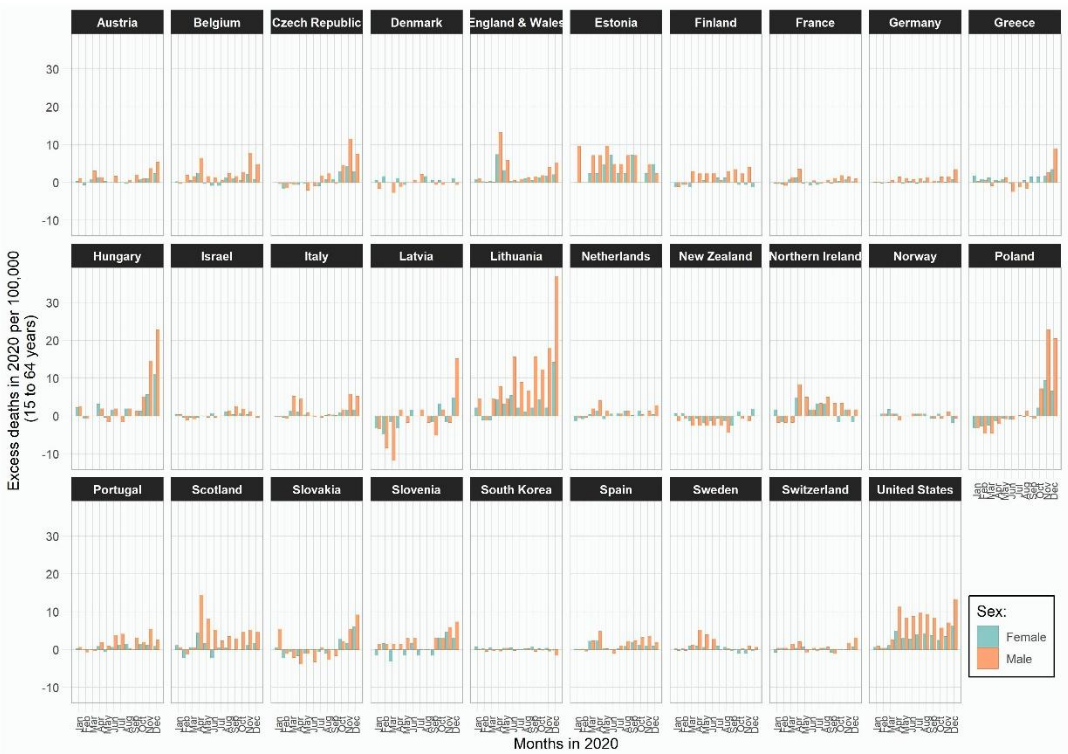


Fig. S1 (C): 65-74 years

Fig. S1 (D): 75-84 years

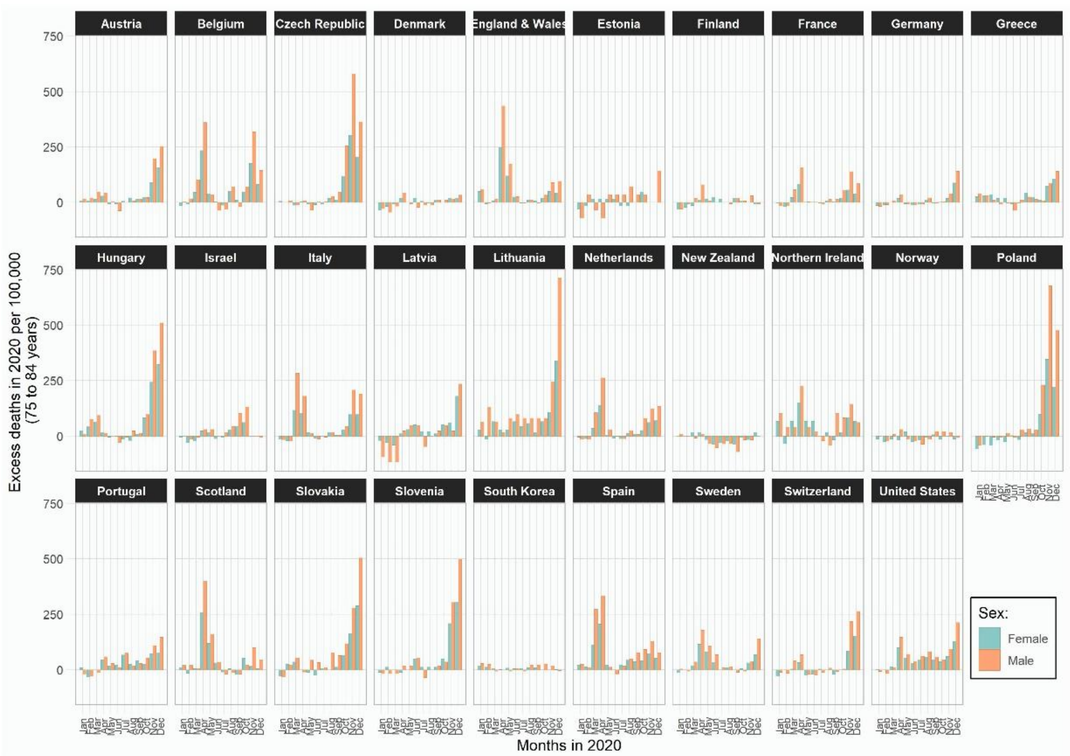


Fig. S1 (E): 85 years or above

Figure S2: Percent change in weekly excess deaths in 2020 by age and sex in 29 high-income countries

Fig. S2 (A): <15 years

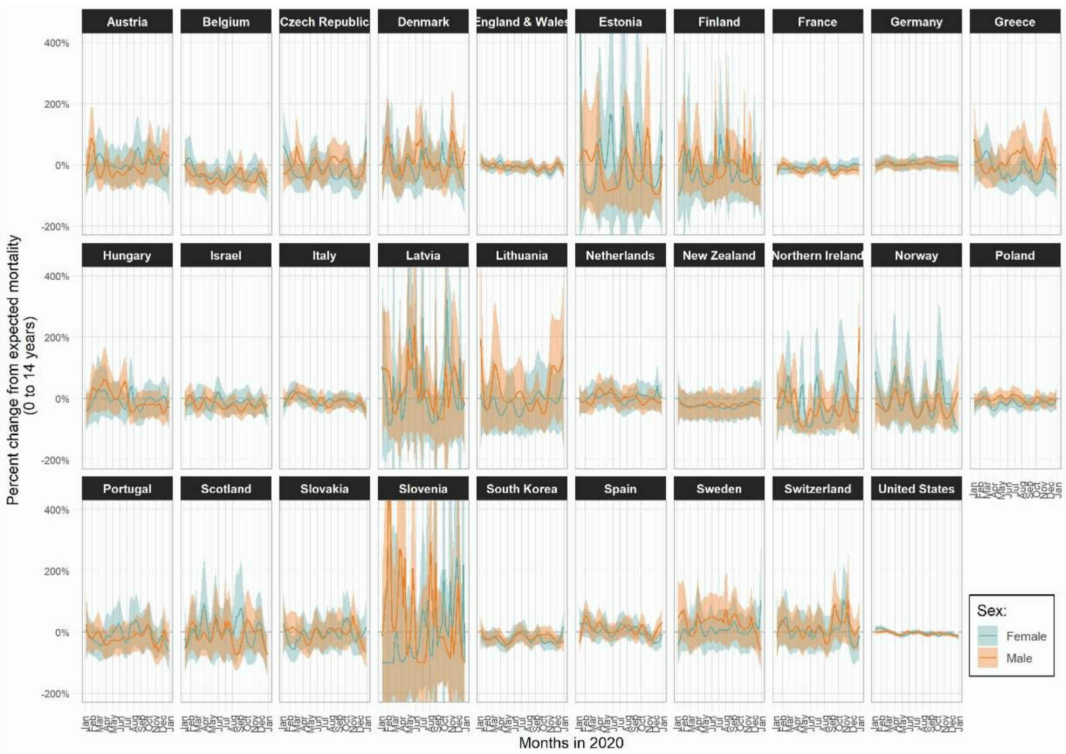


Fig. S2 (B): 15-64 years

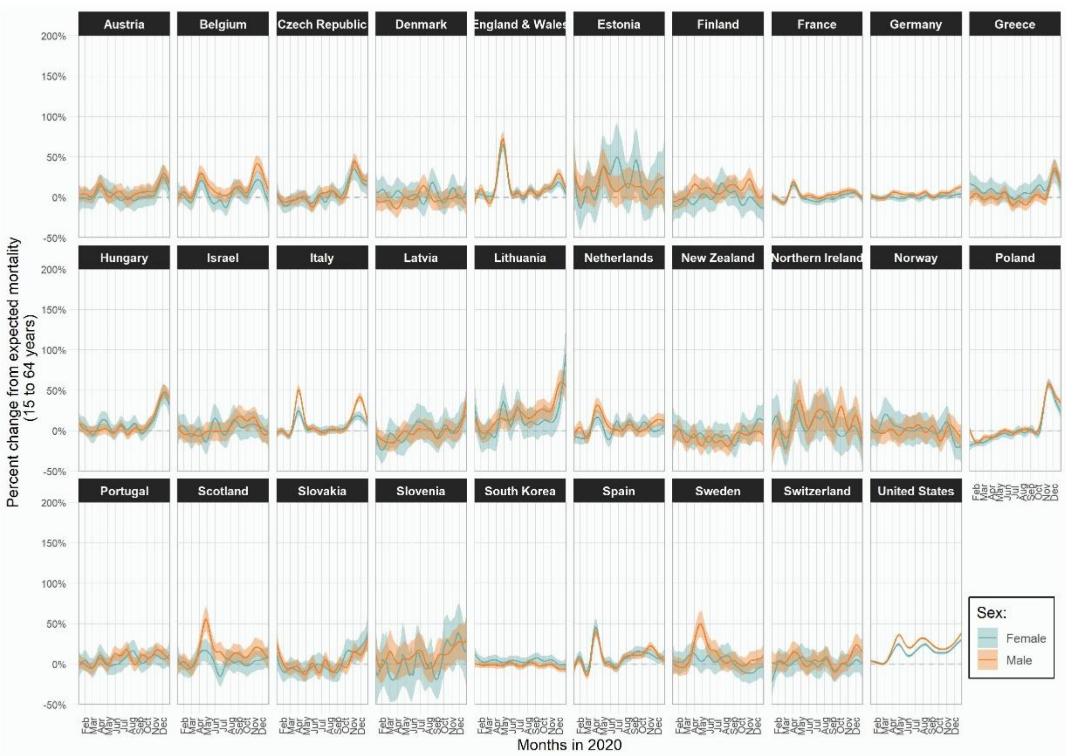


Fig. S2 (C): 65-74 years

Fig. S2 (D): 75-84 years

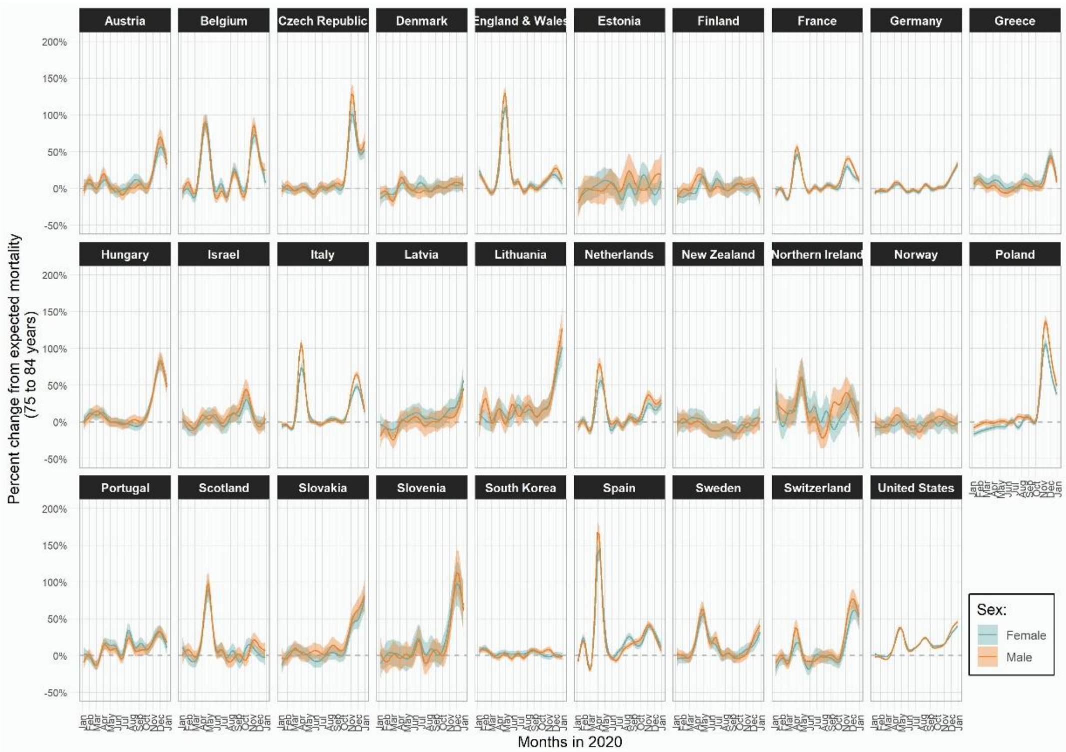


Fig. S2 (E): 85 years or above

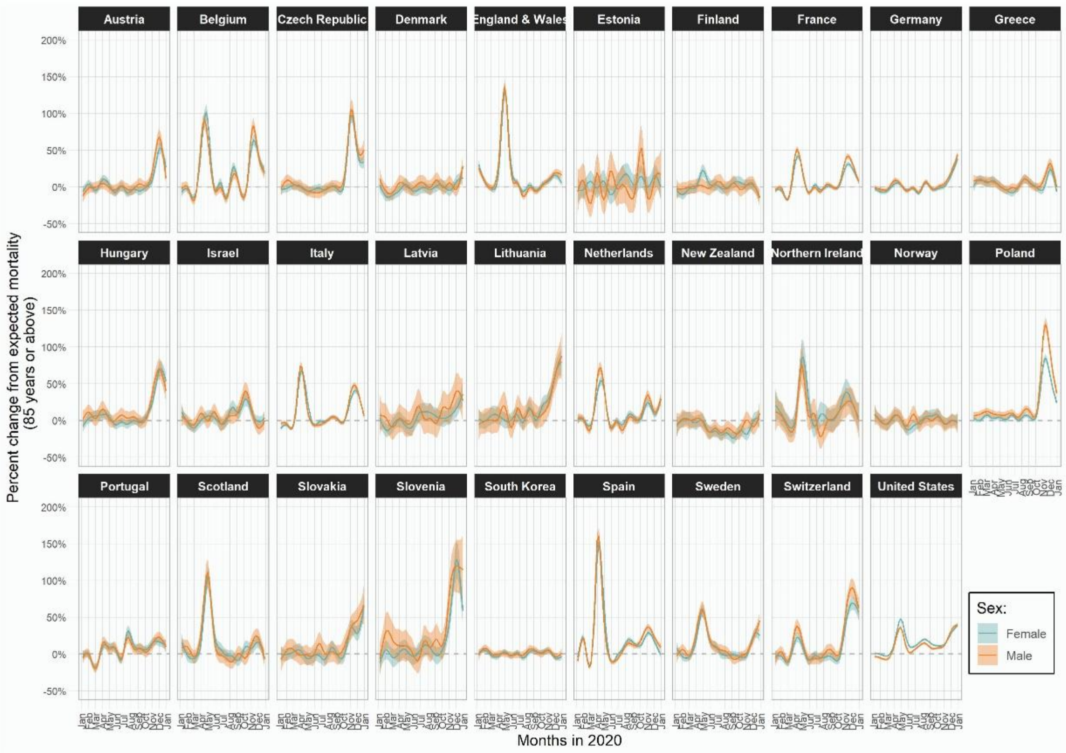


Figure S3: Age-standardised annual mortality rate in men and women in 29 high-income countries, 2016-2020

Fig. S3 (A): Age-standardised annual mortality rate in men and women

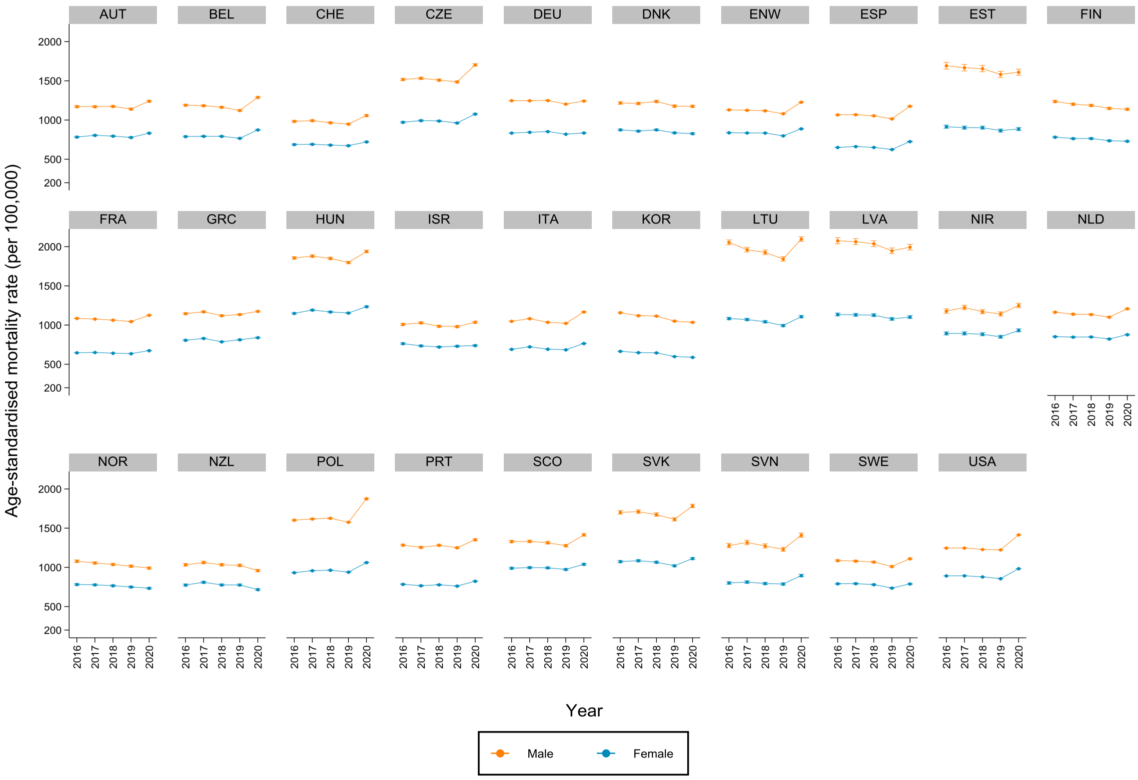
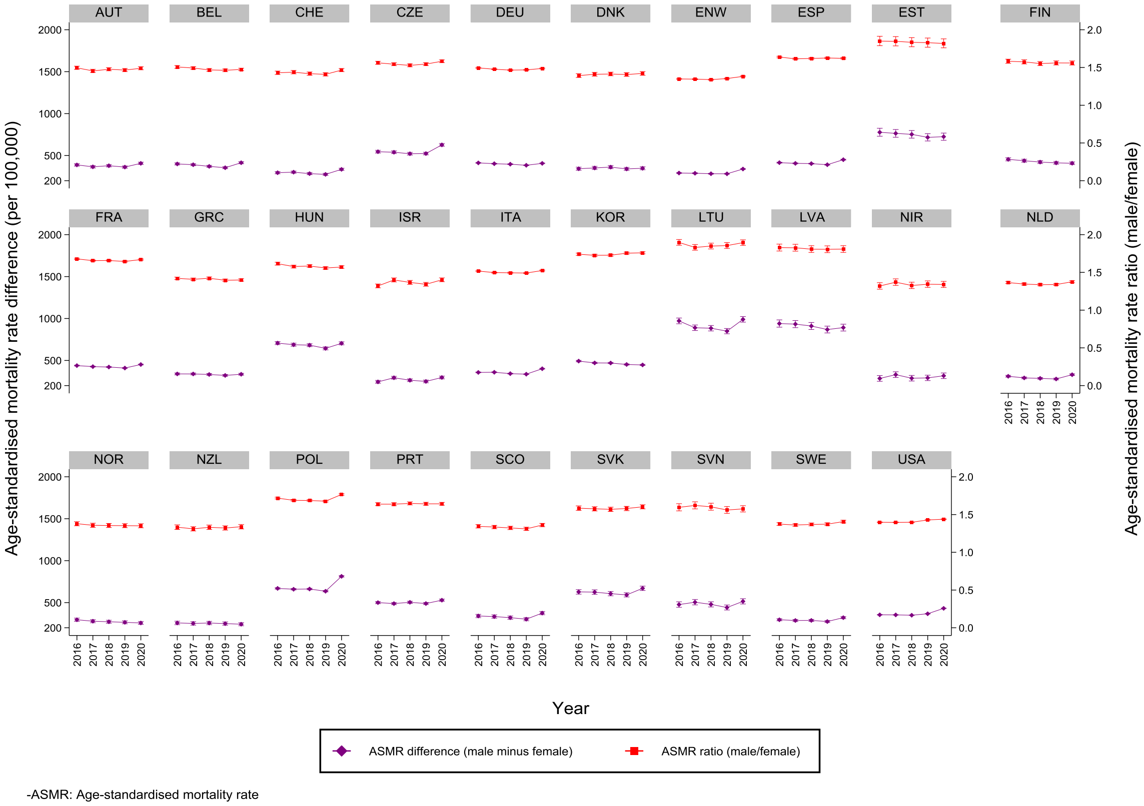


Fig. S3 (B): Age-standardised annual mortality rate difference and ratio between men and women



List of country code and the country names is available in the Supplementary Table S1. The death rates were standardised to the 2013 European Standard Population.

Figure S4: Crude annual mortality rate in 29 high-income countries, 2016-2020

Fig. S4 (A): <15 years

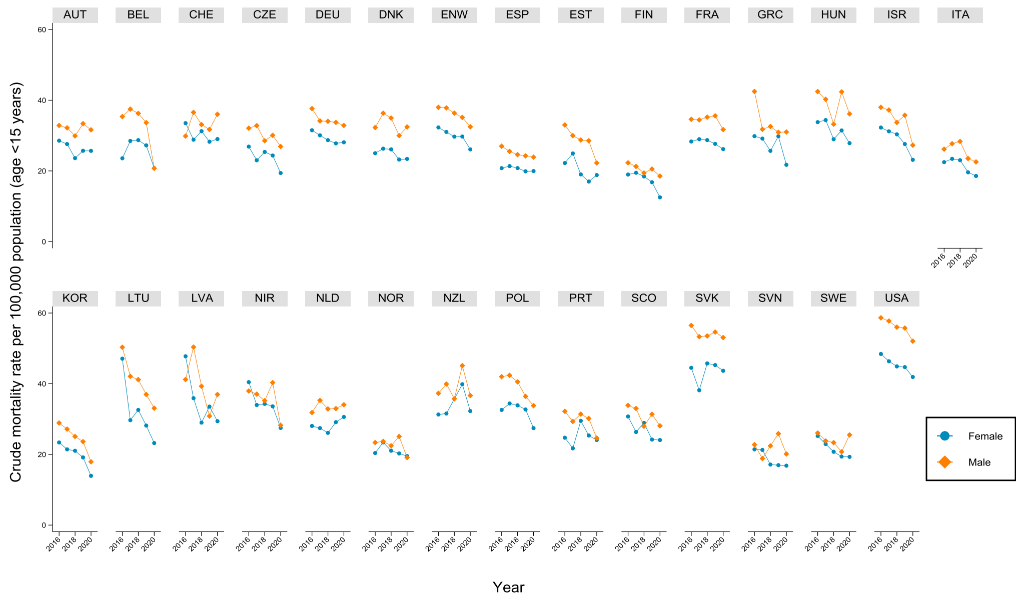


Fig. S4 (B): 15-64 years

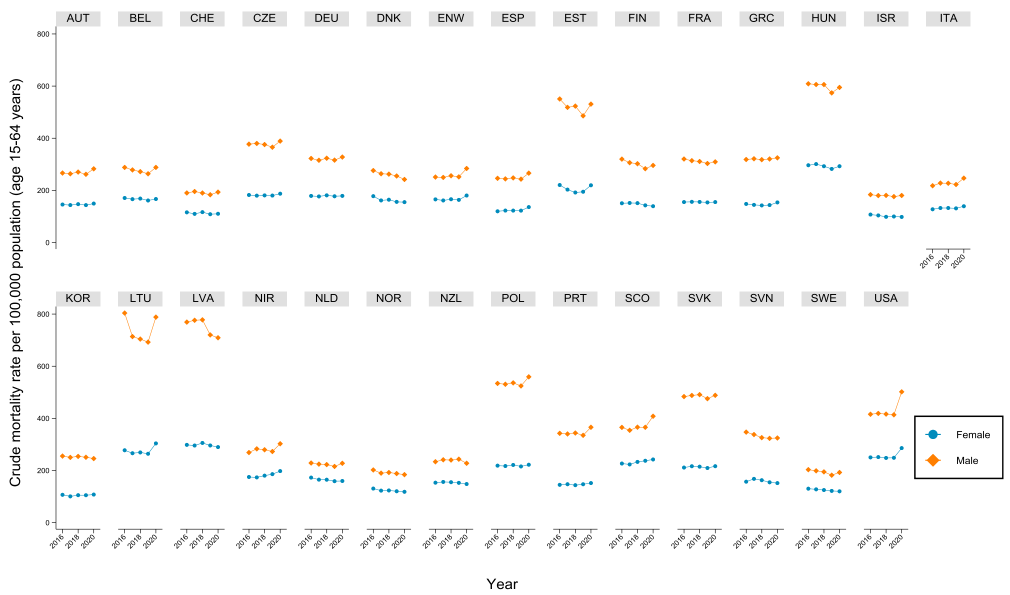


Fig. S4 (C): 65-74 years

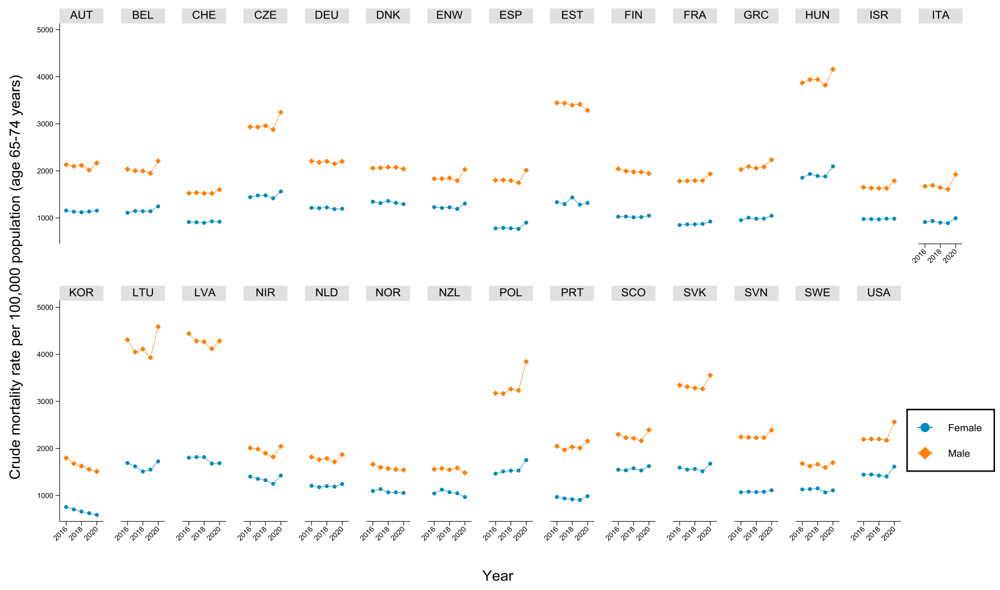


Fig. S4 (D): 75-84 years

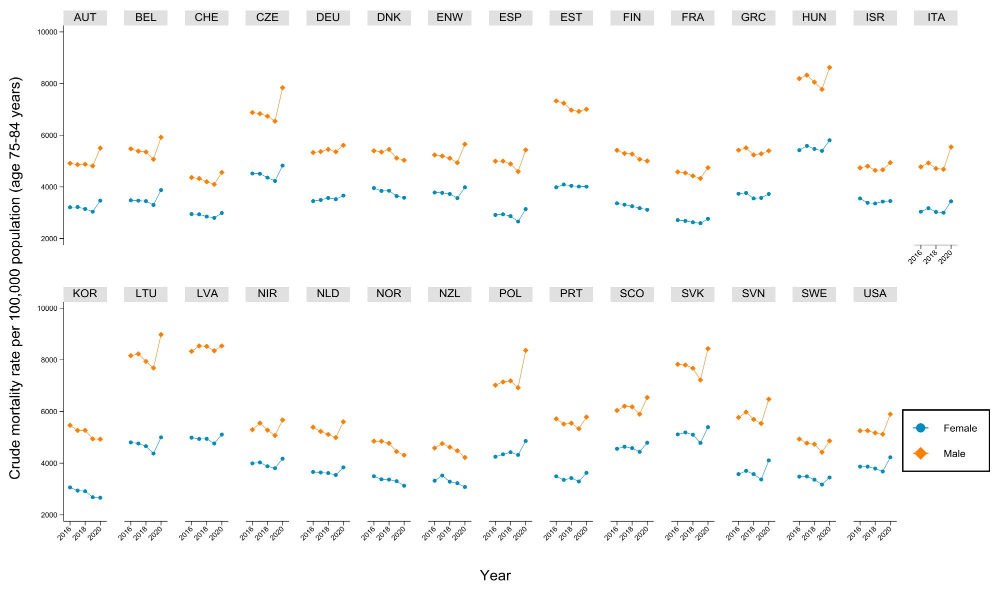


Fig. S4 (E): 85 years or above

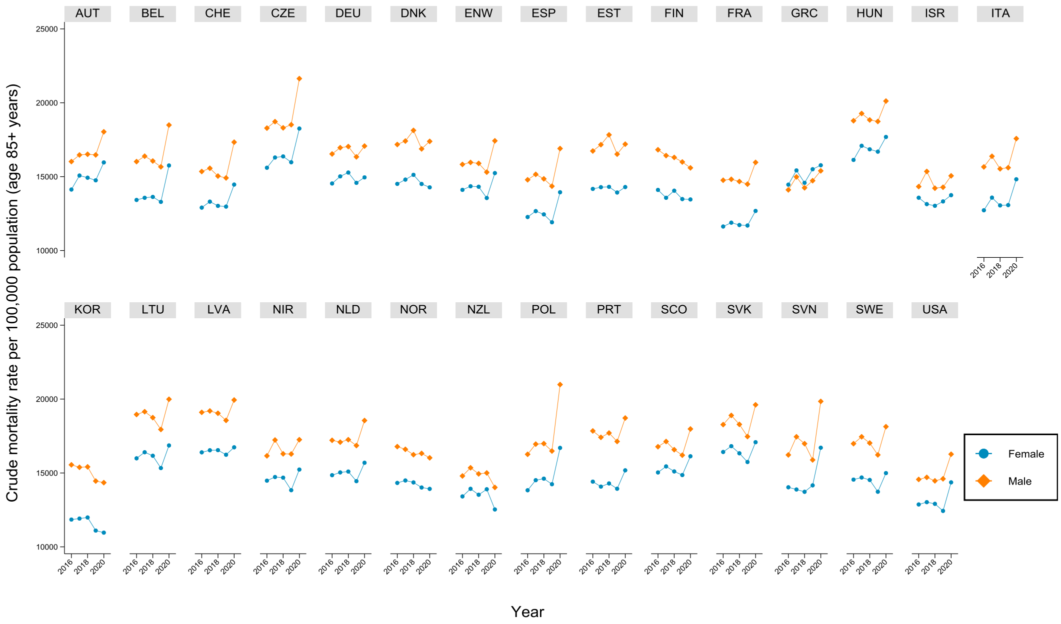


Figure S5: Percent change in weekly excess deaths in 29 high-income countries, 2016-2019

(Shaded regions indicate 95% confidence interval)

Fig. S5 (A): Female

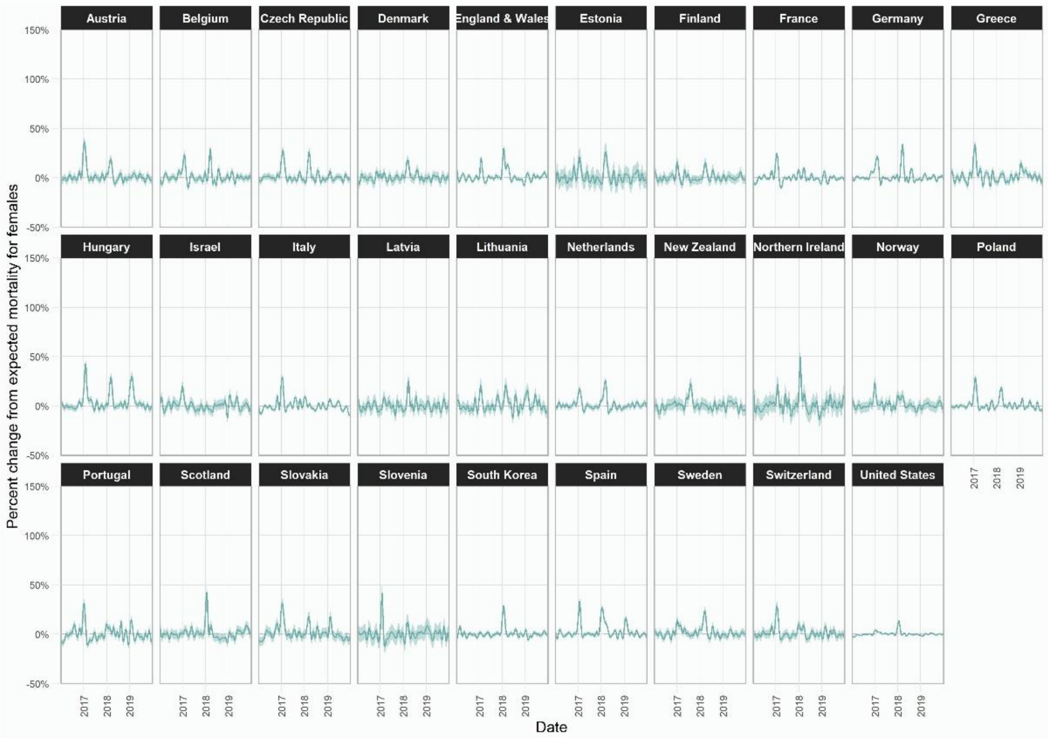


Fig. S5 (B): Male

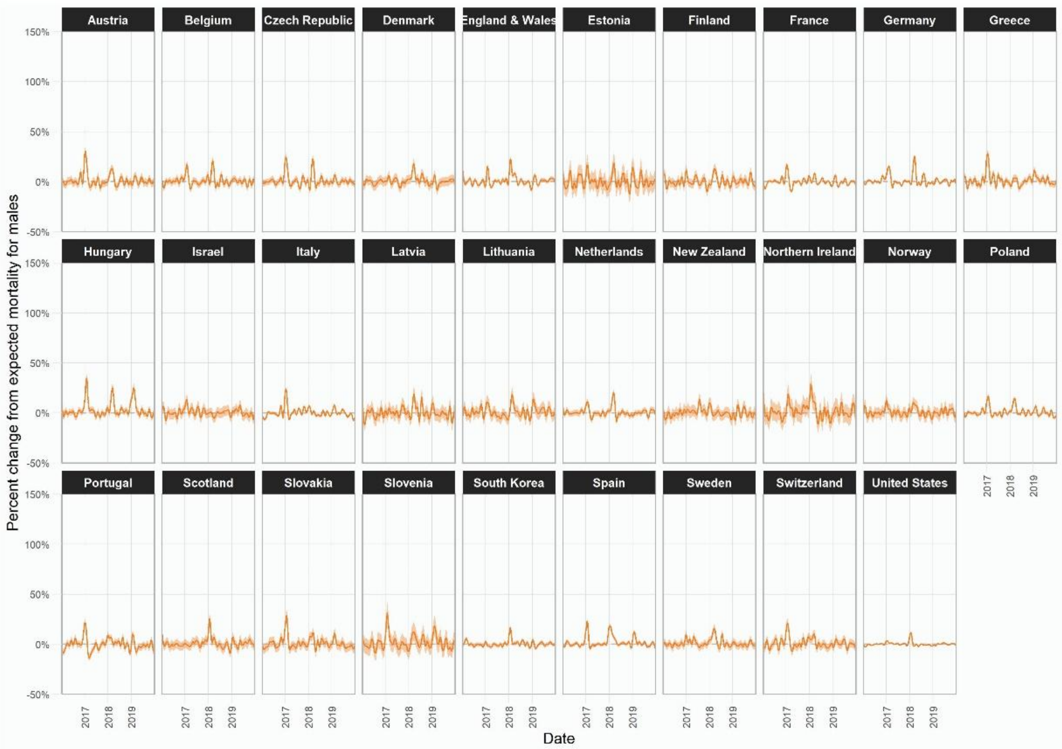


Figure S6: Excess death rates (per 100,000) in 19 high-income countries in 2020 among people 15-64 years, by sex and 10-year age groups

References:

1 European Commission. Eurostat. *Revision of the European Standard Population: report of Eurostat's task force : 2013 edition.* LU: : Publications Office 2013. https://data.europa.eu/doi/10.2785/11470 (accessed 14 Jan 2021).

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