Recent Gains in Life Expectancy Reversed by the COVID-19 Pandemic

José Manuel Aburto[‡,§,*], Jonas Schöley[*], Luyin Zhang[‡,¶], Ilya Kashnitsky[*], Charles Rahal[‡,§], Trifon I. Missov[*], Melinda C. Mills[‡,§], Jennifer B. Dowd[‡,§], Ridhi Kashyap[‡,§,†]

[‡] *Leverhulme Centre for Demographic Science and Department of Sociology, University of Oxford*
[§] *Nuffield College, University of Oxford*
[*] *Interdisciplinary Centre on Population Dynamics, University of Southern Denmark*
[¶] *St. Cross College, University of Oxford*
[†] *School of Anthropology and Museum Ethnography, University of Oxford*

2nd March, 2021

A collaboration between the Interdisciplinary Centre on Population Dynamics, University of Southern Denmark and the Leverhulme Centre for Demographic Science, University of Oxford

Abstract: The COVID-19 pandemic halted longevity improvements and mortality reductions at older ages in 2020. Life expectancy at birth — a widely-used indicator of population health — declined from 2019 to 2020 in 24 out of 26 countries for which high-quality vital statistics are presently available, including most European countries, Chile and the USA. Males in the USA and Bulgaria experienced the largest losses in life expectancy at birth during 2020 (2.1 and 1.6 years respectively), but staggering reductions of more than an entire year were documented in eleven countries for males, and seven among females; a magnitude of loss not witnessed since WW-II in many countries. Reductions were mostly attributable to increased mortality above age 60 and to official COVID-19 deaths.

One-sentence summary: COVID-19 erased years of life expectancy gains in several countries, with the biggest losses for US and Bulgarian males.

Keywords: COVID-19; demography; life expectancy; morbidity; mortality

For correspondence: José Manuel Aburto (jose-manuel.aburto@sociology.ox.ac.uk), Jonas Schöley (jschoeley@health.sdu.dk), and Ridhi Kashyap (ridhi.kashyap@nuffield.ox.ac.uk). The replication files for this paper including customised functions in the statistics environment R are available on Zenodo, a general-purpose open-access repository developed under the European OpenAIRE program and operated by CERN (10.5281/zenodo.4556982). We would like to thank Alyson van Raalte, Jim Oeppen, Christiaan Monden and John Ermisch for their insightful comments on the manuscript. We also thank Ainhoa Alustiza for her timely response on issues related to the STMF dataset. Funding is gratefully acknowledged from the British Academy's Newton International Fellowship grant NIFBA19/190679 (JMA, RK), a Rockwool Foundation's Excess Deaths grant (JMA, JS, TIM, IK), a Leverhulme Trust Large Centre Grant (JMA, LZ, RK, CR, JBD and MCM), Nuffield College (JM, RK, CR, JBD, MCM), John Fell Fund grant 0009182 (JMA, RK, CR, JBD, MCM) and European Research Council grant 835079 (MCM).

MAIN TEXT

More than two million lives are estimated to have been lost due to COVID-19 around the world in 2020 (Dong et al., 2020). This estimate – while staggering – masks the uneven impact of the pandemic across different countries and demographic characteristics like age and sex (Pifarré i Arolas et al., 2021), as well as its impact on population health and longevity (Trias-Llimós et al., 2020). Moreover, variations in testing capacity coupled with definitional inconsistencies in counting COVID-19 deaths make the true global toll of COVID-19 infections difficult to estimate with accuracy (Karlinsky and Kobak, 2021). To address these measurement challenges, significant efforts have been directed at the harmonisation and analysis of all-cause mortality data. A widely-used approach to quantify the burden of the pandemic using all-cause mortality is through the analysis of excess mortality, defined as the number of deaths observed during the pandemic above a baseline of recent trends (Pifarré i Arolas et al., 2021; Aburto et al., 2021). Here we go beyond excess deaths and country-specific analyses and focus on the pressing issue of revealing the impacts of the pandemic on life expectancy in a cross-national perspective.

Life expectancy at birth is the most widely-used metric of population health and longevity. It refers to the average number of years a synthetic cohort of newborns would live if they were to experience the death rates observed in a given period throughout their lifespan. While the indicator does not describe a cohort's actual life course (Goldstein and Lee, 2020) and should not be interpreted as the expected lifespan of any individual (see Supplemental text 2), it summarizes the mortality profile of a population in a given period (Andrasfay and Goldman, 2021; Aburto et al., 2020). As life expectancy is unaffected by the size and age structure of a population, it is the preferred indicator for comparisons over time within and across countries (Andrasfay and Goldman, 2021). Life expectancy can also be calculated as conditional on surviving to a given age, e.g. 60, where it refers to remaining life expectancy from age 60. The study of life expectancy in the context of the COVID-19 pandemic matters because it enables us to compare the cumulative impacts of the pandemic against recent trends across different countries using a standardized indicator that is routinely monitored to capture differences in mortality.

Prior to the pandemic, life expectancy at birth typically increased almost monotonically in most countries over the 20th and 21st centuries (United Nations, 2021). In recent decades, improvements were predominantly driven by gains made at older ages (65+) in high income countries (Aburto et al., 2020), although significant cross-country heterogeneity persists. This heterogeneity has become more prominent since 2010— while some countries in Eastern Europe and the Baltics experienced significant gains in life expectancy in the past decade (Aburto and van Raalte, 2018), others witnessed noticeable slowdowns in the pace of improvements, and in some cases, stalls or even temporary reversal (Ho and Hendi, 2018). For example, life expectancy in the USA (Mehta et al., 2020) and England and Wales saw only limited gains in the last decade (Leon et al., 2019). These atypical trends have been linked to slower improvements in old-age mortality, and increases in working-age death rates (Leon et al., 2019; Ho, 2013).

In a context where trajectories of life expectancy progress became more varied, the COVID-19 pandemic triggered a global mortality crisis posing additional challenges on population health. Deaths from COVID-19 vary by sex, with higher case-fatality rates among older age groups (Levin et al., 2020); precisely those that have accounted for mortality improvements in recent years. The pandemic also indirectly affected mortality from other causes of death. Emerging evidence has highlighted the impacts of delayed treatments or avoidance of care-seeking for cancers or cardiovascular diseases (Hanna et al., 2020; Wu et al., 2021) resulting in increasing mortality from these conditions, while lockdowns may have reduced the number of deaths due to accidents (Calderon-Anyosa and Kaufman, 2021).

This study is the first to use an unprecedented collection of demographic data from 26 countries, representing most of Europe, Chile and the USA, to examine the impacts of the pandemic on life expectancy in 2020, contextualised against trends in 2015-2019. To enable reliable cross-national comparisons of life

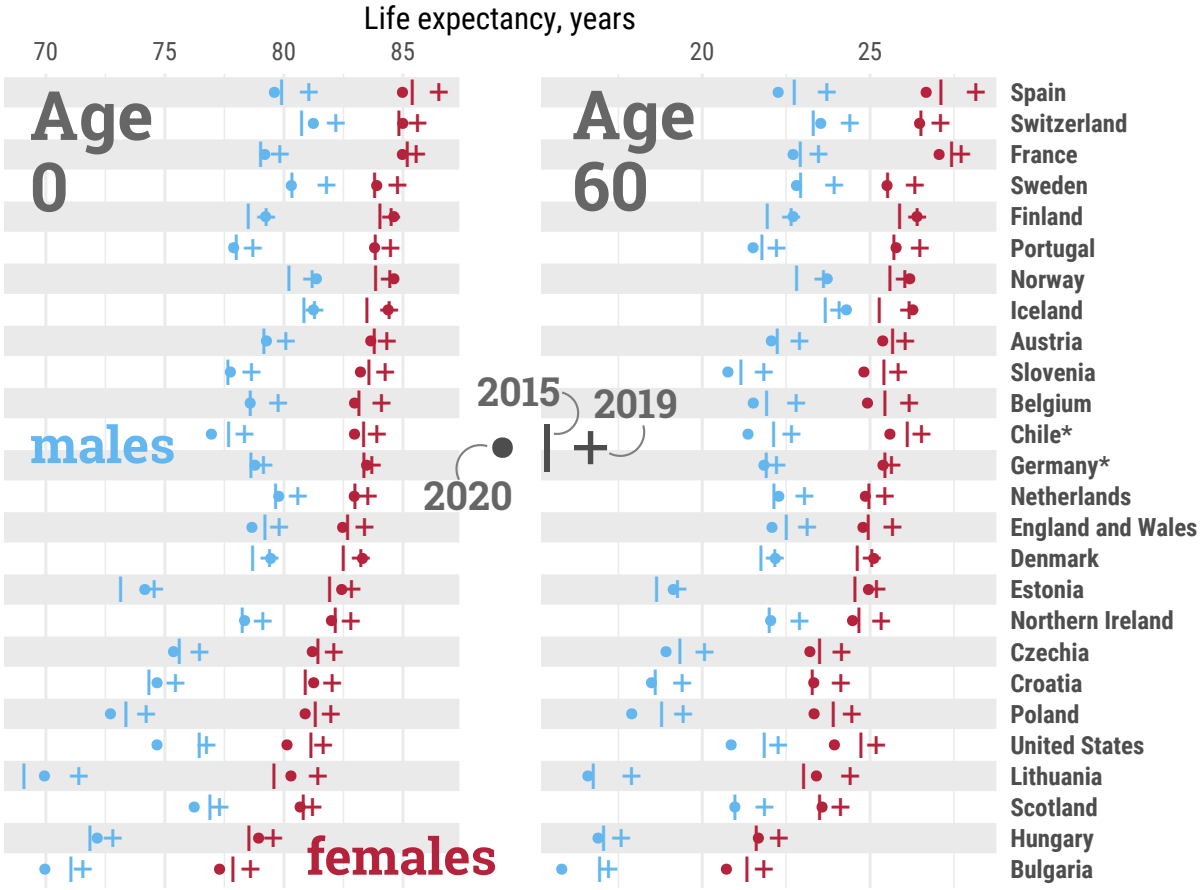

Figure 1: Life expectancy at birth (age 0, left panel) and at age 60 (right panel) by country and sex, in 2015, 2019, and 2020. Note: Estimates for females (red), males (blue), 2015 (|), 2019 (+), 2020 (•). Countries are sorted from highest to lowest levels of female life expectancy at birth in 2019. *Estimates for Chile and Germany were available from 2016.

expectancy over the period 2015-2020, we harmonised death counts and population estimates from multiple sources, leveraging major ongoing efforts collecting data on all-cause mortality (Max Planck Institute for Demographic Research, 2021) and official COVID-19 deaths (Riffe et al., 2021). Only countries with high quality age-disaggregated all-cause mortality data were included to estimate life tables (see Methods). We focus on the pressing questions of how much life expectancy changed in 2020 relative to the period 2015-2019 and whether the impact was different for males and females. Leveraging demographic methods we unravel which age-groups contributed to changes in life expectancy in 2020, and to what extent observed reductions in life expectancy were attributable to officially reported COVID-19 deaths.

In our dataset, life expectancy at birth among females in 2019 ranged from 78.6 years in Bulgaria to 86.5 in Spain (Fig. 1). Among males, it ranged from 71.4 years in Lithuania to 82.2 in Switzerland. At age 60, countries in Eastern Europe and Scotland exhibited the lowest remaining life expectancy, while older females in France and Spain enjoyed the highest. From 2015 to 2019, all countries experienced increases in life expectancy at birth, albeit with varying magnitudes (Fig. 2). Among females, gains ranged from less than a month per year in France and Scotland, to more than 2.5 months in Estonia, Hungary, and Lithuania. Among males, the USA, Scotland, and Iceland had the lowest gains in life expectancy at birth (less than a month per year), while Lithuanian males benefited from more than five months per year of additional life expectancy. Similar trends across countries were observed for life expectancy at age 60, emphasizing the importance of improvements in older age survival.

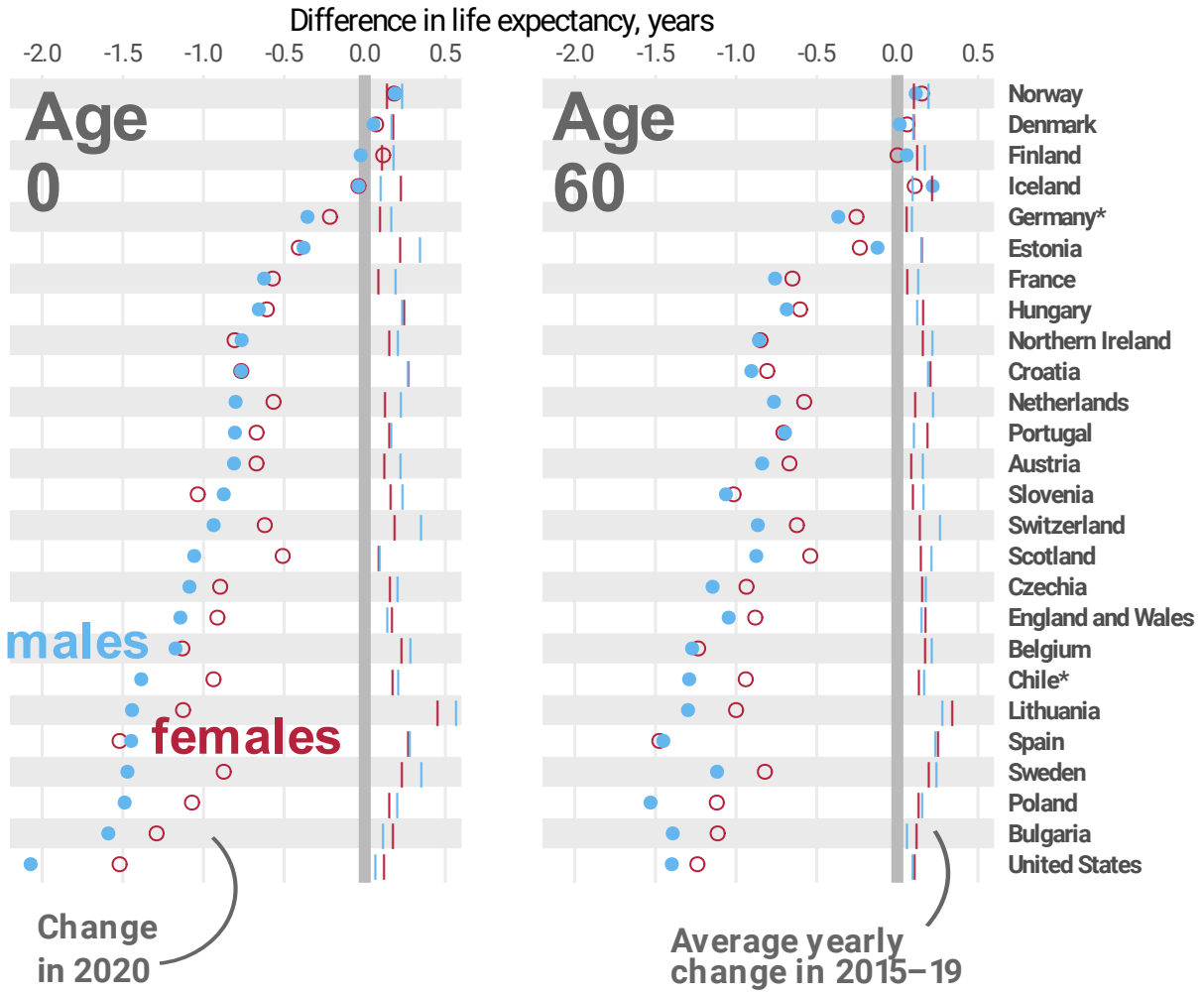

Figure 2: Average per-year change in life expectancy at birth (age 0) and age 60, by country and sex, from 2015 to 2019, and total change from 2019 to 2020. Note: Estimates for females (red), males (blue), average changes from 2015 to 2019 are depicted by the symbol (|), dots (•) depict the total change from 2019 to 2020. Countries are sorted from smallest to largest losses between 2019 to 2020 in male life expectancy at birth. *Estimates for Chile and Germany were available from 2016.

In contrast, life expectancy declined in all countries for both sexes from 2019 to 2020, with the exception of females in Finland and both sexes in Denmark and Norway (Fig. 2). In most countries, males experienced larger losses. The magnitude of these declines offset most gains in life expectancy in the five years prior to the pandemic. Out of 26 countries, females from 14 and males from 10 ended up with lower life expectancy at birth in 2020 than in 2015 (Fig. 1), which was already an exceptionally bad year for life expectancy due to the strong flu season (Ho and Hendi, 2018). Our results show that from 2019 to 2020, females in 7 countries and males in 11 lost in excess of one year of life expectancy at birth —a magnitude of loss not seen since World War II in many countries or the breakup of the Soviet Union in Eastern Europe. The biggest losses of 1.5 years or more of life expectancy at birth were documented among males in the USA, Bulgaria, Poland and Sweden, and females in the USA and Spain. At age 60, remaining life expectancy declined the most (1.5 years) for females in Spain and males in Portugal and Spain.

Mortality reductions are translated into gains in life expectancy at birth and can be attributed to specific age groups. Bars shown in Fig. 3 indicate the contributions, in years, to changes in life expectancy in 2015-2019 and 2019-2020 by broad age groups and sex (finer age grouping in Supplementary Fig. S1). Between

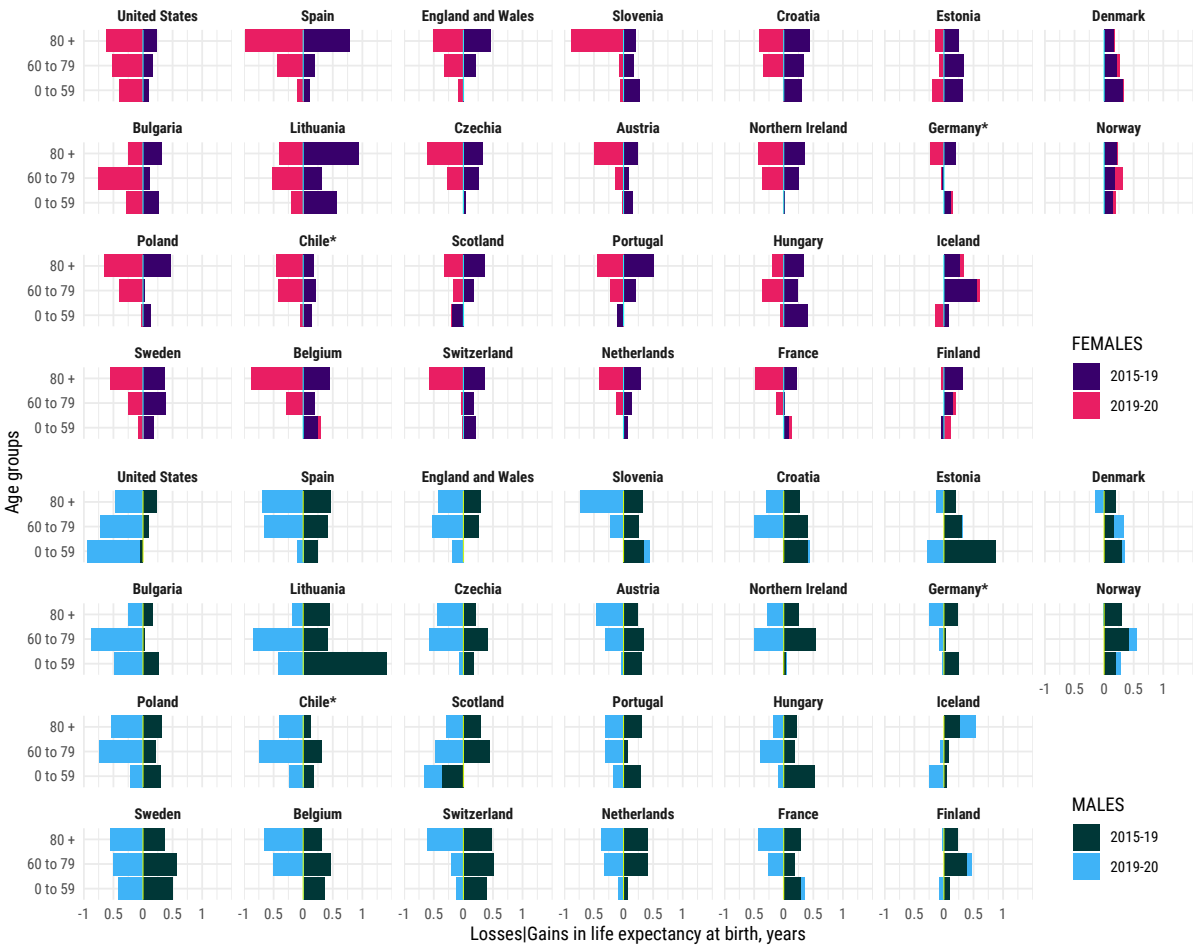

Figure 3: Contributions (in years) to changes in life expectancy at birth from 2015 to 2019, and from 2019 to 2020, attributable to mortality below age 60, from 60 to 80, and above age 80, by country and sex. Note: Positive values indicate gains in life expectancy, negative values indicate reductions in life expectancy. The sum of contributions over age results in the total change of life expectancy at birth during the specific period. Countries are sorted (column-wise) from largest to smallest losses between 2019 to 2020 in male life expectancy at birth.*Estimates for Chile and Germany were available from 2016.

2015-2019, mortality improvements above age 60 consistently contributed to increasing life expectancy across countries. In several countries, life expectancy gains above age 80 surpassed those in the age group 60-79. Improvements below age 60 contributed less, but progress was still observed in many countries, especially in Eastern Europe, with the exception of the USA and Scotland where life expectancy decreased due to worsening mortality at these ages.

The COVID-19 pandemic led to sharp declines in life expectancy (see Fig. 2), predominantly due to elevated mortality in the older age groups (see Fig. 3). Increased death rates above age 60 contributed the most to life expectancy declines across all countries between 2019 and 2020. While for females across most countries increased death rates at ages 80+ contributed most to life expectancy losses, among females in Eastern Europe worsening mortality at ages 60-79 contributed more to the decline. Among males elevated death rates at ages 60-79 contributed most to life expectancy losses across most countries, but the impact of mortality below age 60 was noticeable in many countries, especially those suffering the biggest losses in life expectancy. For example, males below age 60 in the USA contributed the most to decreasing life expectancy between 2019 and 2020.

We were able to quantify the contribution of registered COVID-19 deaths to life expectancy reductions

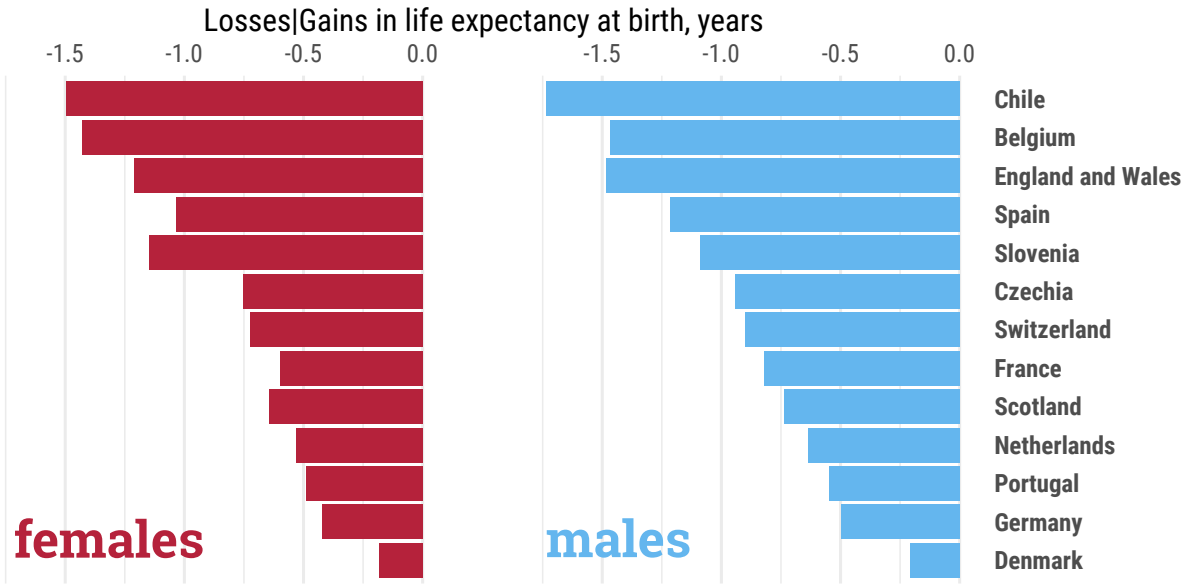

Figure 4: Contributions (in years) to changes in life expectancy at birth from 2019 to 2020 attributable to official COVID-19 deaths. Note: Countries are sorted from largest to smallest losses..

for 13 countries (Fig. 4) for which more reliable age and sex-disaggregated data on COVID-19 deaths were available (see Methods). However, we acknowledge issues linked to the potential misclassification of COVID-19 deaths such that these estimates may not fully capture the true direct impact of COVID-19 (see Supplementary text 1). Despite these caveats, we estimated that deaths reported as COVID-19 in the COVerAGE database (Riffe et al., 2021) explain the majority of life expectancy losses observed. Both females and males in Chile, England Wales, Belgium, Spain and Slovenia experienced losses of more than a whole year of life expectancy at birth due to COVID-19 official deaths, explaining most of the overall loss between 2019 and 2020. To put this into perspective, it took on average 5.6 years for these countries to achieve a one-year increase in life expectancy recently (Barbieri et al., 2015), a progress wiped out over the course of 2020 by COVID-19. In some contexts, such as Denmark and Chile, we note that life expectancy losses due to COVID-19 deaths were larger than total life expectancy losses, as increased mortality due to COVID-19 was offset by mortality reductions among non-COVID causes.

Our analyses show that the pandemic exacted a striking toll on population health in 2020, reversing progress in life expectancy from recent years in many countries. Emerging evidence from some developing countries (such as Brazil and Mexico) which have been devastated by the pandemic (Karlinsky and Kobak, 2021) suggests that life expectancy losses may be even larger in these populations. Similarly, losses in life expectancy are likely to vary substantially between subgroups within countries, with recent research from the US showing socially disadvantaged groups experiencing losses three times higher than those reported here at the national level (Andrasfay and Goldman, 2021; Arias et al., 2021). However, a lack of data currently limits direct and more dis-aggregated comparisons, but these are urgently needed to understand the full mortality impacts of the pandemic. With further data, researchers can examine the causes of these uneven mortality impacts of the pandemic within and across countries, including differences in underlying co-morbidities, health care systems, and non-pharmaceutical interventions. While COVID-19 might be seen as a transient shock to life expectancy, the evidence of potential long-term morbidity due to long-COVID and impacts of delayed care for other illnesses (Hanna et al., 2020; Wu et al., 2021), as well as health effects and widening inequalities stemming from the social and economic disruption of the pandemic (Bambra

et al., 2020) suggest that the scars of the COVID-19 pandemic on population health may be longer lasting.

MATERIALS AND METHODS

Data

All-cause death counts were retrieved from the Short Term Mortality Fluctuations (STMF) data series within the Human Mortality Database (HMD) (Max Planck Institute for Demographic Research, 2021). Additional all-cause mortality data were retrieved for the USA from the CDC (Centers for Disease Control and Prevention, 2021) and for England Wales from the ONS (Office for National Statistics, 2021) to supplement the STMF data. STMF provides high-quality weekly death counts for 38 countries (at the time of writing) in both a harmonized and original format, but the completeness of these data varies by country. We processed the original input files and selected 24 countries for further analysis. Countries with weeks missing from the 2020 death tabulation or with coarse age grouping schemes were dropped from the analysis (see Table S1). Death counts for the USA and England Wales across the years 2015 to 2019 were only reported in extremely coarse age groups by the STMF, but were available in fine grouping for 2020. For both countries we therefore utilized age-specific annual death counts as reported by the CDC (Centers for Disease Control and Prevention, 2021) and the ONS (Office for National Statistics, 2021) for the years prior to 2020. All-cause mortality data were supplemented with COVID-19 deaths from the COVerAGE-DB database for a subset of 13 countries with sufficient quality in their reported COVID-19 deaths and with at least 50 weeks of information (Riffe et al., 2021). COVerAGE-DB provides information about COVID-19 confirmed cases and deaths to confirmed cases as reported by statistical agencies for over 100 countries, in a standardized format with harmonized age groups. Population estimates were retrieved from the United Nations for the years 2015-2020; and for the year 2020 we used age-specific mid-year population projections from World Population Prospects 2019 (United Nations, 2021). For England Wales, Northern Ireland and Scotland, mid-year population estimates from HMD for the year 2018 were projected for 2019 and 2020 using stable population assumptions (see Supplementary Fig. S2). We opted against official projections because the WPP does not disaggregate the UK into its constituent countries, and the oldest age group in ONS projections is 90+.

Methods

All-cause mortality data are available in irregular age groups for different countries. We harmonized data from STMF, CDC, ONS and COVerAGE-DB using a penalized composite link model (PCLM) which estimated death counts in single years of age from 0 to 110 from the grouped data (Rizzi et al., 2015; Pascariu et al.). The PCLM model was fitted independently to each country, sex, and year combination, and the smoothing parameters were estimated via a Bayesian Information Criteria based grid search. Prior to ungrouping we summed the weekly death counts from the STMF data into annual death counts, also taking into account deaths reported in unknown weeks. In cases where the age grouping changed from one week to the next, we first summed all the deaths within a stratum and year belonging to the same age grouping scheme, applied PCLM ungrouping separately for each scheme and then summed the ungrouped deaths into annual counts by single years of age.

Person years of exposure were approximated by estimated or projected mid-year population counts and used in the denominator of the age-specific death rates. Exposure estimates were adjusted for leap-weeks as most countries in the STMF data report deaths using the ISO week date calendar (International Organization for Standardization, 2021). The length of a year in the ISO week calendar is either 371 days in

a leap-week year such as 2020, or 364 days in a regular year such as 2019. Thus, the longer reporting interval for leap-week years would, other things equal, increase observed death counts by a factor of 371/364=1.9 over regular years. To counter this spurious effect we adjusted the exposures by the factor 371/364 in ISO week date leap years. This adjustment has been made for all countries analyzed in this paper with the exception of annual deaths prior to 2020 for the US and England Wales, which have been reported over a Gregorian year by the CDC and ONS sources.

Life table construction

Life tables for all 26 countries by sex for the period 2015-2020 were constructed following a piece-wise constant hazard model using all-cause mortality by single age with the last age interval grouping deaths at ages 85+, consistent with standard demographic techniques (Preston et al., 2001). Our choice of grouping deaths above age 85+ is common practice in demographic research, and it ensures comparability across countries, especially because some countries used this last age group to report deaths for 2020. The choice of the last open ended interval may impact estimates of life expectancy depending on the proportion of the population surviving to this last interval (31). To evaluate its impact, we further calculated life tables by grouping death counts estimated from the PCLM model above age 100+ for countries where more granular age categorisation was available (See Supplementary Fig. S3). Populations that were smaller were more sensitive to the choice of the last open-ended group. However, trends in life expectancy remained similar. From these life tables, life expectancy at birth and life expectancy conditional on surviving to age 60 for males and females were extracted for each country by sex. Life expectancy estimates are commonly reported and compared on a yearly basis. We performed several sensitivity checks to ensure the robustness of our estimates including comparisons with alternative sources such as the United Nations and from the Human Mortality Database for the period from 2015 to 2019, or their most recent year available (see Supplementary Fig. S3). Additionally, we compared full year death counts in our estimates with those reported in the HMD for previous years (Supplementary Fig. S4). Most countries did not show deviations across sources, with the exception of Sweden and Austria, where the STMF underestimates death counts varying from 2% and 4% for females and males, respectively. We further calculated life expectancy using the death counts from both sources and WPP population estimates as exposures and found that the effect on life expectancy is negligible (less than 1%). For the USA, we also compared our life expectancy estimates with those based on provisional data up to June 2020 (Arias et al., 2021). Our results show a sharper decrease of life expectancy than those based on mid-year estimates, in line with including the remaining months of 2020 that also saw persistent levels of excess mortality.

Decomposition of life expectancy by age and cause of death

In order to disentangle age-specific effects and to quantify the impact of COVID-19 deaths on changes in life expectancy, we used the linear integral decomposition method (Horiuchi et al., 2008), a state-of-the-art method that allows us to decompose the difference of two values of life expectancy by age and cause of death, which has been implemented previously for this type of analysis (Aburto and van Raalte, 2018). This methodology assumes that causes of death are exhaustive and independent. This assumption may not be realistic in the context of COVID-19, as the pandemic may have indirectly affected other causes of death. However, previous evidence suggests that the net effect of interactions between causes of death are negligible in decomposition analysis (Beltrán-Sánchez et al., 2008). Moreover, our results are likely to be unaffected by this assumption since most COVID-19 deaths are excess deaths. In addition, in most countries the contribution of COVID-19 deaths to changes in life expectancy can be interpreted as a lower bound due to late registration and testing strategies for COVID-19. We decompose yearly changes in life

expectancy by age and deaths registered as COVID-19 versus the rest of deaths for each country by age and sex. This methodology has the advantage that the resulting estimates are additive and the total change in a given period, such as 2015-2019, is the sum of yearly estimates from 2015 to 2019. As a sensitivity check we replicated our results with step-wise decomposition method(Andreev et al., 2002). Results from this sensitivity check show that most of the changes were a result of increased mortality at older ages as our method reported.

SUPPLEMENTARY TEXT 1

Limitations

There are several limitations of our approach. While most of the countries included in our analysis have high-quality systems of death registration and usually report timely and complete death counts(Barbieri et al., 2015), there are likely issues related to delays in death registration in 2020. We deal with these potential issues by harmonizing and smoothing death counts with a penalized composite link model which has been shown to provide reliable estimates of mortality for all countries in our study (Rizzi et al., 2015), and by adjusting the person-years exposed to the risk of death depending on the full-weeks reported in the STMF. In most STMF countries, deaths that take place in a given week are covered by more than 90% by the following two weeks (STMF metadata). Therefore, we expect the percentage of missing deaths in the last weeks of 2020 to be low. Moreover, according to the SMTF metadata, some countries (such as Austria, England and Wales, Germany, and the Netherlands) employ extrapolation procedures to correct for incompleteness to adjust for missing deaths counts in the preceding 1-to-3 weeks. We recognise nonetheless that late and/or under registration may affect our estimates by underestimating losses in 2020. Therefore our results should be interpreted as estimates of the lower bound of life expectancy reductions in 2020. For COVID-19 official mortality figures, there are likely to be inaccuracies due to differences in classification and testing practices across countries. While we are unable to precisely measure the extent to which these inaccuracies may affect our estimates to make adjustments (i.e., since misclassification can occur for different reasons), we err on the side of caution and interpret our results as a lower bound of the impact of COVID-19 deaths on changes in life expectancy.

The magnitude of life expectancy losses can also be influenced by migration due to COVID-19, especially in countries where persistent out-migration flows are not tracked accurately (via population registers) between censuses. For example, in Eastern European countries with high levels of out-migration in their populations, increased mortality could have occurred as a result of elevated return migration due to the COVID-19 pandemic. Nevertheless, we anticipate that the magnitude of these effects is likely to be small in size due to the broadly younger age profiles of migrants and previous evidence that suggests that mortality at younger ages is more likely to be affected by international migration (Rogers and Castro, 1981). In 2020, as increased mortality occurred mostly at older ages, the effect of migration on our estimates is likely to be low. Despite these limitations, we used the most reliable data for all countries included in the study to gauge the contributions of age and COVID-19 to changes in life expectancy across countries, sex, and over time.

SUPPLEMENTARY TEXT 2

Interpretation of life expectancy

Life expectancy is a widely-used but often misinterpreted indicator of a population's mortality profile that is computed using a mathematical model. The model employed to calculate life expectancy is known as life table. As with any model it is based on assumptions. Life expectancy at birth is the average number

of years a synthetic cohort of newborns would live if along the course of their lives they were to experience the age-specific death rates observed in a given time or period. This indicator is thus often referred to as 'period life expectancy', as it simulates and summarizes the implications of a current period. This is in contrast to a cohort measure that would track the longevity of a group of people born at the same time. The key advantage of period life expectancy, which results in its routine use and monitoring, is that it is an age-standardized indicator that allows comparisons between populations of different sizes and age structures, and across space and over time. Period life expectancy is not to be interpreted as a projection nor a forecast, and neither does it describe a cohort's actual life course. It is purely a summary measure of the age-specific mortality profile of a population.

Authors contributions: Conceptualization: JMA, JS, RK. Data curation: JS, LZ, JMA, RK, TIM, IK. Formal analysis: JMA, JS, LZ, IK. Methodology: JMA, RK, JS, IK. Software: JS, JMA, LZ, IK. Visualization: IK, JS, CR, JMA, RK, JBD, MCM. Project administration: JMA, RK. Supervision: JMA, RK, JS. Drafting: JMA, RK. Review and editing: LZ, JS, IK, TIM, CR, JBD, MCM.

Data and materials availability: The replication files for this paper include customised functionality written in the R statistical programming language (R. Core Team, 2013). The code, and all harmonized input and output data pertaining to our analysis, is hosted both on Zenodo (a general-purpose open-access repository developed under the European OpenAIRE program and operated by CERN) at https://zenodo.org/record/4556982, and on GitHub (https://github.com/oxforddemsci/ex2020).

REFERENCES

Jose Manuel Aburto, Ridhi Kashyap, Jonas Schöley, Colin Angus, John Ermisch, Melinda C. Mills, and Jennifer Beam Dowd. Estimating the burden of the COVID-19 pandemic on mortality, life expectancy and lifespan inequality in England and Wales: A population-level analysis. *J Epidemiol Community Health*, 2021. ISSN 0143-005X, 1470-2738. doi: 10.1136/jech-2020-215505. URL https://jech.bmj.com/content/early/2021/01/18/jech-2020-215505.

José Manuel Aburto and Alyson van Raalte. Lifespan Dispersion in Times of Life Expectancy Fluctuation: The Case of Central and Eastern Europe. *Demography*, 55(6):2071–2096, 2018. ISSN 0070-3370, 1533-7790. doi: 10.1007/s13524-018-0729-9. URL http://link.springer.com/10.1007/s13524-018-0729-9.

José Manuel Aburto, Francisco Villavicencio, Ugofilippo Basellini, Søren Kjærgaard, and James W. Vaupel. Dynamics of life expectancy and life span equality. *Proceedings of the National Academy of Sciences*, 117(10):5250–5259, 2020. ISSN 0027-8424, 1091-6490. doi: 10.1073/pnas.1915884117. URL http://www.pnas.org/lookup/doi/10.1073/pnas.1915884117.

Theresa Andrasfay and Noreen Goldman. Reductions in 2020 US life expectancy due to COVID-19 and the disproportionate impact on the Black and Latino populations. *Proceedings of the National Academy of Sciences*, 118(5), 2021. ISSN 0027-8424, 1091-6490. doi: 10.1073/pnas.2014746118. URL https://www.pnas.org/content/118/5/e2014746118.

Evgeny M. Andreev, Vladimir M. Shkolnikov, and Alexander Begun. Algorithm for decomposition of differences between aggregate demographic measures and its application to life expectancies, healthy life expectancies, parity-progression ratios and total fertility rates. *Demographic Research*, 7(14):499–522, 2002. ISSN 1435-9871. doi: 10.4054/DemRes.2002.7.14. URL https://www.demographic-research.org/volumes/vol7/14/.

Elizabeth Arias, Betzaida Tejada-Vera, and Farida Ahmad. Provisional Life Expectancy Estimates for January through June, 2020, 2021. URL https://dx.doi.org/10.15620/cdc:100392.

Clare Bambra, Ryan Riordan, John Ford, and Fiona Matthews. The COVID-19 pandemic and health inequalities. *J Epidemiol Community Health*, 74(11):964–968, 2020. ISSN 0143-005X, 1470-2738. doi: 10.1136/jech-2020-214401. URL https://jech.bmj.com/content/74/11/964.

Magali Barbieri, John R Wilmoth, Vladimir M Shkolnikov, Dana Glei, Domantas Jasilionis, Dmitri Jdanov, Carl Boe, Timothy Riffe, Pavel Grigoriev, and Celeste Winant. Data Resource Profile: The Human Mortality Database (HMD). *International Journal of Epidemiology*, 44(5):1549–1556, 06 2015. ISSN 0300-5771. doi: 10.1093/ije/dyv105. URL https://doi.org/10.1093/ije/dyv105.

Hiram Beltrán-Sánchez, Samuel H Preston, and Vladimir Canudas-Romo. An integrated approach to cause-of-death analysis: cause-deleted life tables and decompositions of life expectancy. *Demographic research*, 19:1323, July 2008. ISSN 1435-9871. doi: 10.4054/demres.2008.19.35. URL https://europepmc.org/articles/PMC2822405.

Renzo J. C. Calderon-Anyosa and Jay S. Kaufman. Impact of COVID-19 lockdown policy on homicide, suicide, and motor vehicle deaths in Peru. *Preventive Medicine*, 143:106331, 2021. ISSN 0091-7435. doi: 10.1016/j.ypmed.2020.106331. URL http://www.sciencedirect.com/science/article/pii/S0091743520303625.

Centers for Disease Control and Prevention. Underlying Cause of Death, 1999-2019 Request, 2021. URL https://wonder.cdc.gov/ucd-icd10.html.

E. Dong, H. Du, and L. Gardner. An interactive web-based dashboard to track COVID-19 in real time. *The Lancet Infectious Diseases*, 20(5):533–534, 2020. ISSN 14733099. doi: 10.1016/S1473-3099(20)30120-1. URL https://linkinghub.elsevier.com/retrieve/pii/S1473309920301201.

Joshua R. Goldstein and Ronald D. Lee. Demographic perspectives on the mortality of COVID-19 and other epidemics. *Proceedings of the National Academy of Sciences*, 2020. ISSN 0027-8424, 1091-6490. doi: 10.1073/pnas.2006392117. URL https://www.pnas.org/content/early/2020/08/19/2006392117.

Timothy P. Hanna, Will D. King, Stephane Thibodeau, Matthew Jalink, Gregory A. Paulin, Elizabeth Harvey-Jones, Dylan E. O'Sullivan, Christopher M. Booth, Richard Sullivan, and Ajay Aggarwal. Mortality due to cancer treatment delay: Systematic review and meta-analysis. *BMJ*, 371, 2020. ISSN 1756-1833. doi: 10.1136/bmj.m4087. URL https://www.bmj.com/content/371/bmj.m4087.

Jessica Y. Ho. Mortality Under Age 50 Accounts For Much Of The Fact That US Life Expectancy Lags That Of Other High-Income Countries. *Health Affairs*, 32(3):459–467, 2013. ISSN 0278-2715. doi: 10.1377/hlthaff.2012.0574. URL https://www.healthaffairs.org/doi/full/10.1377/hlthaff.2012.0574.

Jessica Y. Ho and Arun S. Hendi. Recent trends in life expectancy across high income countries: Retrospective observational study. *BMJ*, 362, 2018. ISSN 0959-8138, 1756-1833. doi: 10.1136/bmj.k2562. URL https://www.bmj.com/content/362/bmj.k2562.

Shiro Horiuchi, John R Wilmoth, and Scott D Pletcher. A decomposition method based on a model of continuous change. *Demography*, 45(4):785—801, November 2008. ISSN 0070-3370. doi: 10.1353/dem.0.0033. URL https://europepmc.org/articles/PMC2832329.

International Organization for Standardization. ISO week date, 2021. URL https://en.wikipedia.org/w/index.php?title=ISO_week_date&oldid=1007765520.

Ariel Karlinsky and Dmitry Kobak. The World Mortality Dataset: Tracking excess mortality across countries during the COVID-19 pandemic. *medRxiv*, page 2021.01.27.21250604, 2021. doi: 10.1101/2021.01.27.21250604. URL https://www.medrxiv.org/content/10.1101/2021.01.27.21250604v1.

David A Leon, Dmitry A Jdanov, and Vladimir M Shkolnikov. Trends in life expectancy and age-specific mortality in England and Wales, 1970–2016, in comparison with a set of 22 high-income countries: An analysis of vital statistics data. *The Lancet Public Health*, 4(11):e575–e582, 2019. ISSN 2468-2667.

doi: 10.1016/S2468-2667(19)30177-X. URL http://www.sciencedirect.com/science/article/pii/S246826671930177X.

Andrew T. Levin, William P. Hanage, Nana Owusu-Boaitey, Kensington B. Cochran, Seamus P. Walsh, and Gideon Meyerowitz-Katz. Assessing the age specificity of infection fatality rates for COVID-19: Systematic review, meta-analysis, and public policy implications. *European Journal of Epidemiology*, 35 (12):1123–1138, 2020. ISSN 1573-7284. doi: 10.1007/s10654-020-00698-1. URL https://doi.org/10.1007/s10654-020-00698-1.

Max Planck Institute for Demographic Research. Short-term Mortality Fluctuations (STMF) data series. Human Mortality Database., 2021. URL https://www.mortality.org/.

Neil K. Mehta, Leah R. Abrams, and Mikko Myrskylä. US life expectancy stalls due to cardiovascular disease, not drug deaths. *Proceedings of the National Academy of Sciences*, 117(13):6998–7000, 2020. ISSN 0027-8424, 1091-6490. doi: 10.1073/pnas.1920391117. URL https://www.pnas.org/content/117/13/6998.

Office for National Statistics. Deaths registered in England and Wales - Office for National Statistics, 2021. URL https://www.ons.gov.uk/peoplepopulationandcommunity/birthsdeathsandmarriages/deaths/datasets/deathsregisteredinenglandandwalesseriesdrreferencetables.

Marius D. Pascariu, Maciej J. Dańko, Jonas Schöley, and Silvia Rizzi. 'ungroup': An R package for efficient estimation of smooth distributions from coarsely binned data. *Journal of Open Source Software*, 3(29): 937. ISSN 2475-9066. doi: 10.21105/joss.00937. URL https://joss.theoj.org/papers/10.21105/joss.00937.

Héctor Pifarré i Arolas, Enrique Acosta, Guillem López-Casasnovas, Adeline Lo, Catia Nicodemo, Tim Riffe, and Mikko Myrskylä. Years of life lost to COVID-19 in 81 countries. *Scientific Reports*, 11 (1):3504, 2021. ISSN 2045-2322. doi: 10.1038/s41598-021-83040-3. URL https://www.nature.com/articles/s41598-021-83040-3.

S Preston, Patrick Heuveline, and M Guillot. *Measuring and modeling population processes*. Wiley-Blackwell, 2001.

R. Core Team. *R: A Language and Environment for Statistical Computing*. Vienna, Austria, 2013.

Tim Riffe, Enrique Acosta, and COVerAGE-DB project team. COVerAGE-DB: A database of age-structured COVID-19 cases and deaths — medRxiv, 2021. URL https://www.medrxiv.org/content/10.1101/2020.09.18.20197228v2.

Silvia Rizzi, Jutta Gampe, and Paul H. C. Eilers. Efficient Estimation of Smooth Distributions From Coarsely Grouped Data. *American Journal of Epidemiology*, 182(2):138–147, 2015. ISSN 0002-9262, 1476-6256. doi: 10.1093/aje/kwv020. URL https://academic.oup.com/aje/article-lookup/doi/10.1093/aje/kwv020.

Andrei Rogers and Luis J. Castro. Model migration schedules. 1981.

Sergi Trias-Llimós, Tim Riffe, and Usama Bilal. Monitoring life expectancy levels during the COVID-19 pandemic: Example of the unequal impact of the first wave on Spanish regions. *PLOS ONE*, 15(11): e0241952, 2020. ISSN 1932-6203. doi: 10.1371/journal.pone.0241952. URL https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0241952.

United Nations. World Population Prospects - Population Division - United Nations, 2021. URL https://population.un.org/wpp/Download/Standard/Population/.

Jianhua Wu, Mamas A. Mamas, Mohamed O. Mohamed, Chun Shing Kwok, Chris Roebuck, Ben Humberstone, Tom Denwood, Thomas Luescher, Mark A. de Belder, John E. Deanfield, and Chris P. Gale. Place and causes of acute cardiovascular mortality during the COVID-19 pandemic. *Heart*, 107(2):113–119, 2021. ISSN 1355-6037, 1468-201X. doi: 10.1136/heartjnl-2020-317912. URL https://heart.bmj.com/content/107/2/113.

Supplementary Tables

	All cause death counts					Covid deaths	
Country	# Groups		Miss.	Open-age		Latest report	**Notes**
	2019	2020	2020	2019	2020	2020	
Austria	19	19	0	90	90	31/12/2020	
Australia	5	5	5	85	85	31/12/2020	Coarse ages. Missing weeks.
Belgium	19	19	0	90	90	31/12/2020	
Bulgaria	19	19	0	90	90	29/11/2020	
Canada	4	4	7	85	85	/	Coarse ages. Missing weeks.
Switzerland	19	19	0	90	90	31/12/2020	
Chile	20	20	0	95	95	31/12/2020	No data for 2015.
Czech Republic	19	19	0	90	90	31/12/2020	
Germany	15	15	0	95	95	31/12/2020	No data for 2015.
Denmark	21	21	0	100	100	31/12/2020	
Estonia	19	19	0	90	90	13/12/2020	
Spain	19	19	0	90	90	31/12/2020	
Finland	19	19	0	90	90	31/12/2020	
France	21	21	0	95	90	31/12/2020	Some weeks 19 age-groups.
England & Wales	106	20	0	100	90	25/12/2020	Pre-2020 data from ONS.
Northern Ireland	19	19	0	90	85	/	2 weeks with 7 age-groups.
Scotland	20	21	0	90	95	31/12/2020	
Greece[	19	19	3	90	90	31/12/2020	Missing weeks. No data 2015.
Croatia	19	19	0	90	90	20/12/2020	
Hungary	19	19	0	90	90	29/11/2020	
Israel	8	8	0	80	80	28/12/2020	Coarse ages.
Iceland	19	19	0	90	90	29/11/2020	
Italy	22	22	4	100	90	29/12/2020	Missing weeks. Some 19 age-groups.
South Korea	5	5	0	85	85	28/06/2020	Coarse age grouping.
Lithuania	19	19	0	90	90	29/11/2020	
Luxembourg	19	19	0	90	90	20/12/2020	Adolescent hazard anomaly 2019.
Latvia	19	19	0	90	90	29/11/2020	Adolescent hazard anomaly 2019.
Netherlands	19	19	0	90	90	27/12/2020	
Norway	21	21	0	100	100	18/06/2020	
New Zealand	3	3	0	80	80	/	Coarse age grouping.
Poland	19	19	0	90	90	20/12/2020	
Portugal	19	19	0	90	90	31/12/2020	
Russia	19	/	53	90	/	/	No data for 2020.
Sweden	19	19	0	90	90	/	
Slovenia	19	19	0	90	90	31/12/2020	
Slovakia	19	19	1	90	90	20/12/2020	Missing weeks for 2020.
Taiwan	21	21	1	100	100	10/08/2020	Missing weeks for 2020.
USA	11	11	0	85	85	26/12/2020	Pre-2020 data from CDC.

Table S1: Data quality of raw all-cause and Covid-19 death data. Note: Source data retrieved 2021-02-26 from HMD-STMF, CoverAge-DB, UK-ONS, and US-CDC. All cause death counts from STMF unless stated otherwise in the notes. Countries noted in italics were excluded from analysis. Countries in bold are part of COVID-19 analysis. Number of age groups refers to at least 90% of the weeks in the input data for a given year. 'Miss' denotes missing weeks in 2020.

Supplementary Figures

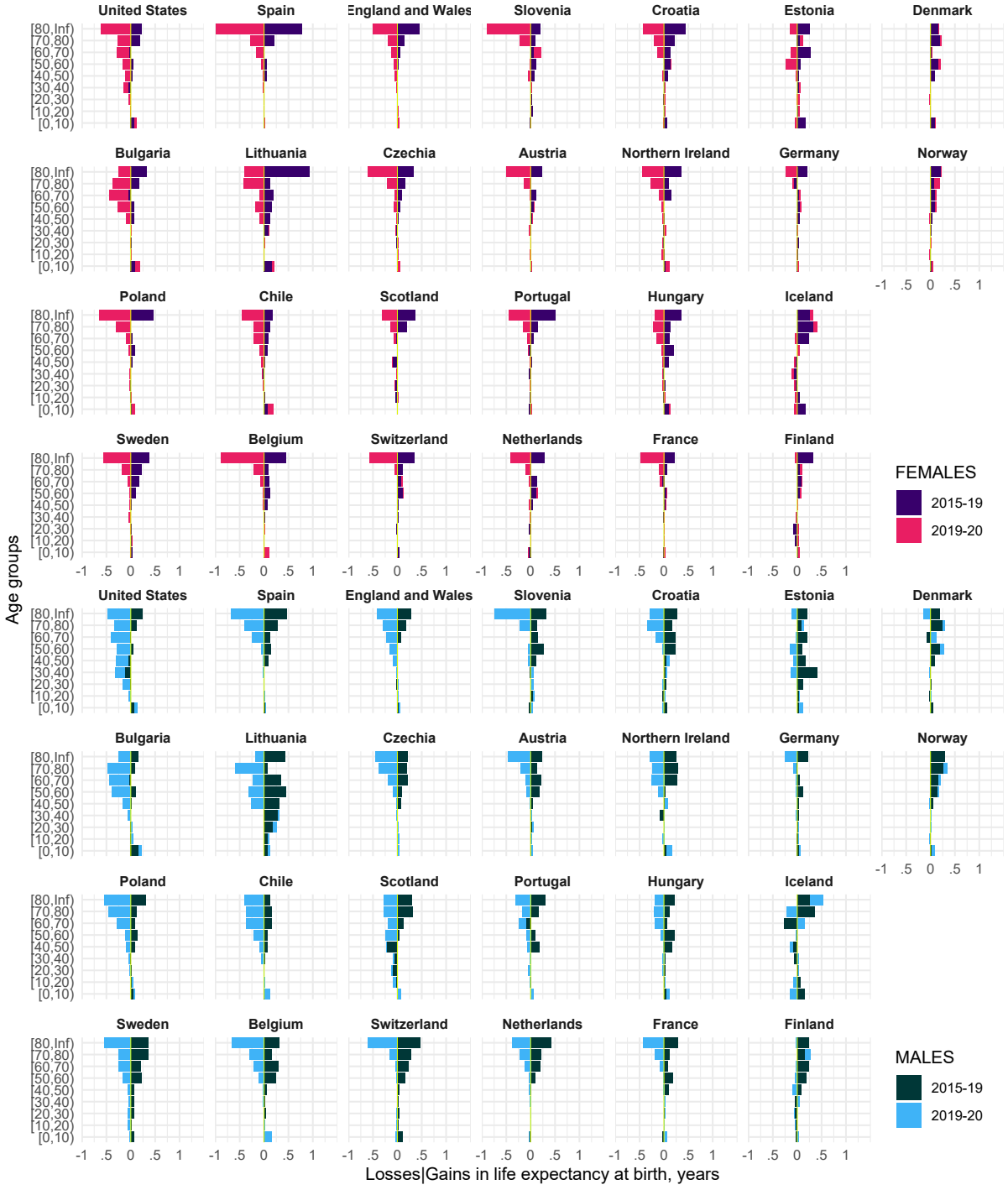

Figure S1: Contributions (in years) to changes in life expectancy at birth from 2015 to 2019, and from 2019 to 2020, attributable to mortality in different 10-year age groups by country and sex. Note: Positive values indicate gains in life expectancy, negative values indicate reductions in life expectancy. *Estimates for Chile and Germany were available from 2016.

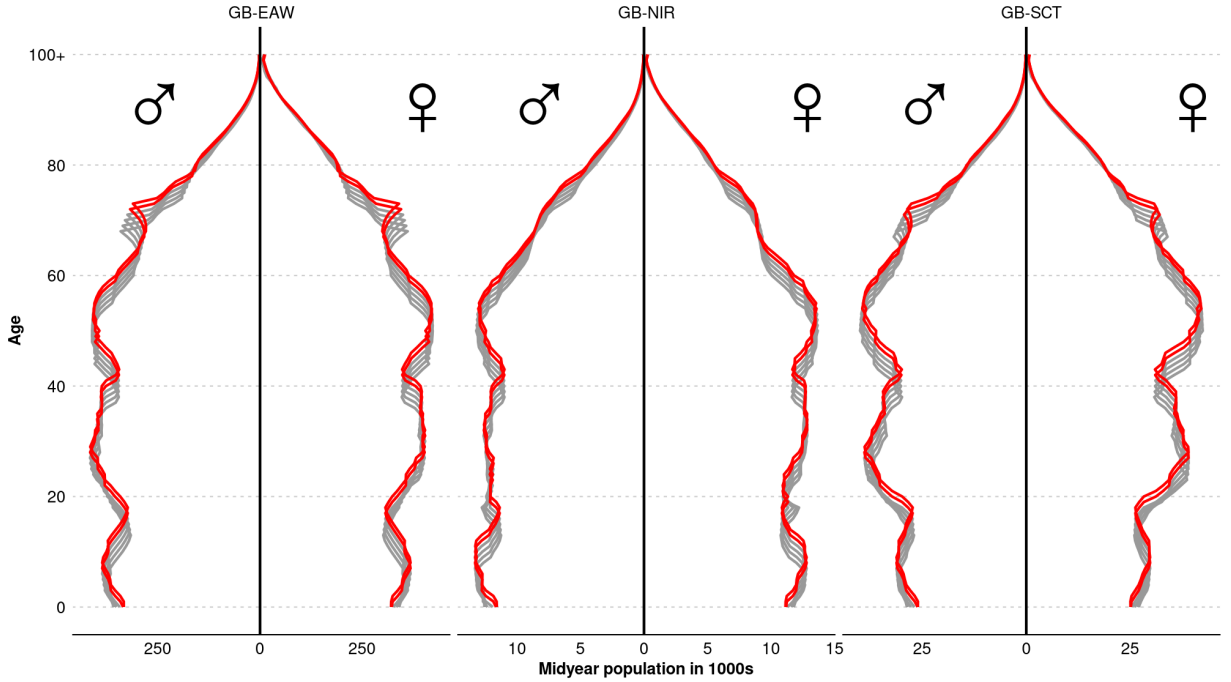

Figure S2: Midyear population by age 2015-2018 as reported by the Human Mortality Database and own projections for 2019-2020 for England Wales, Scotland and Northern Ireland.

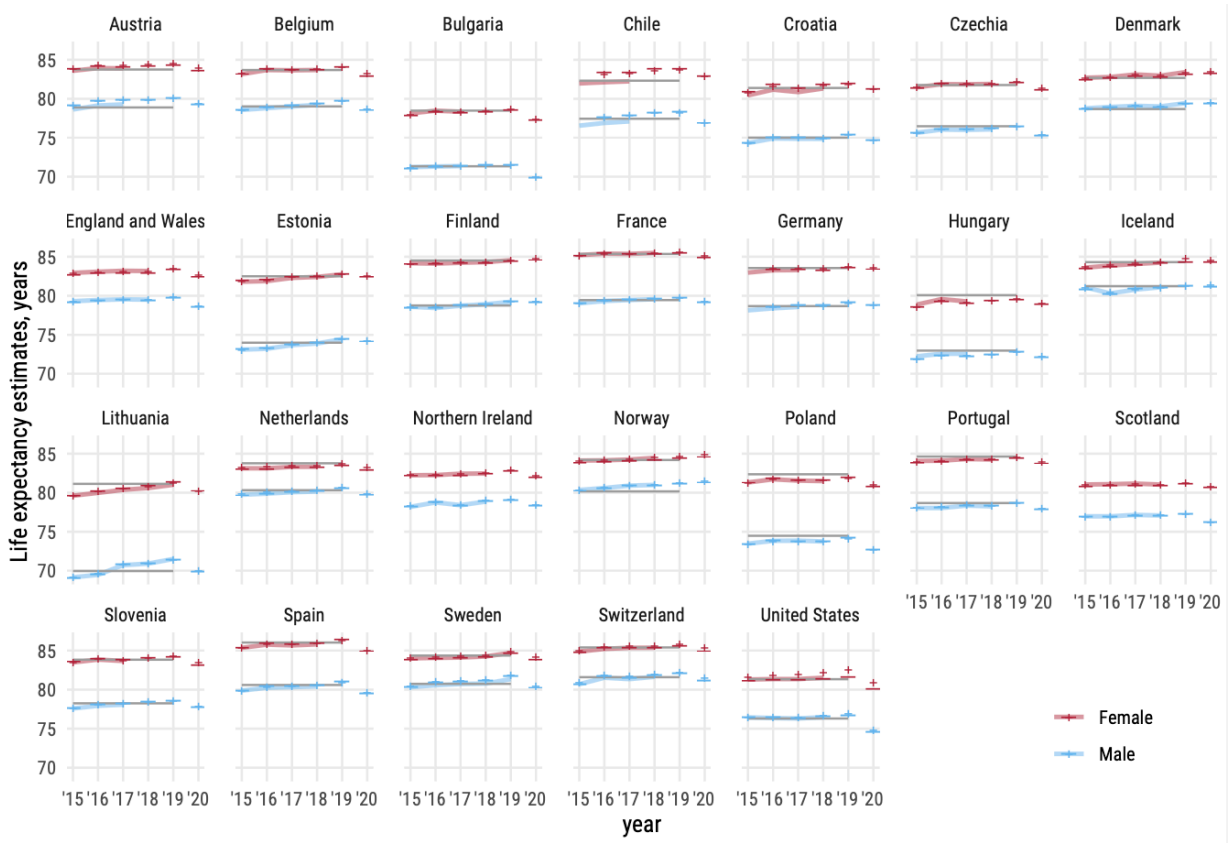

Figure S3: Comparison of estimates of life expectancy by closing life tables at 85+ and 100+ with those published by the United Nations and the Human Mortality Database in the period 2015-19 or most updated year available.

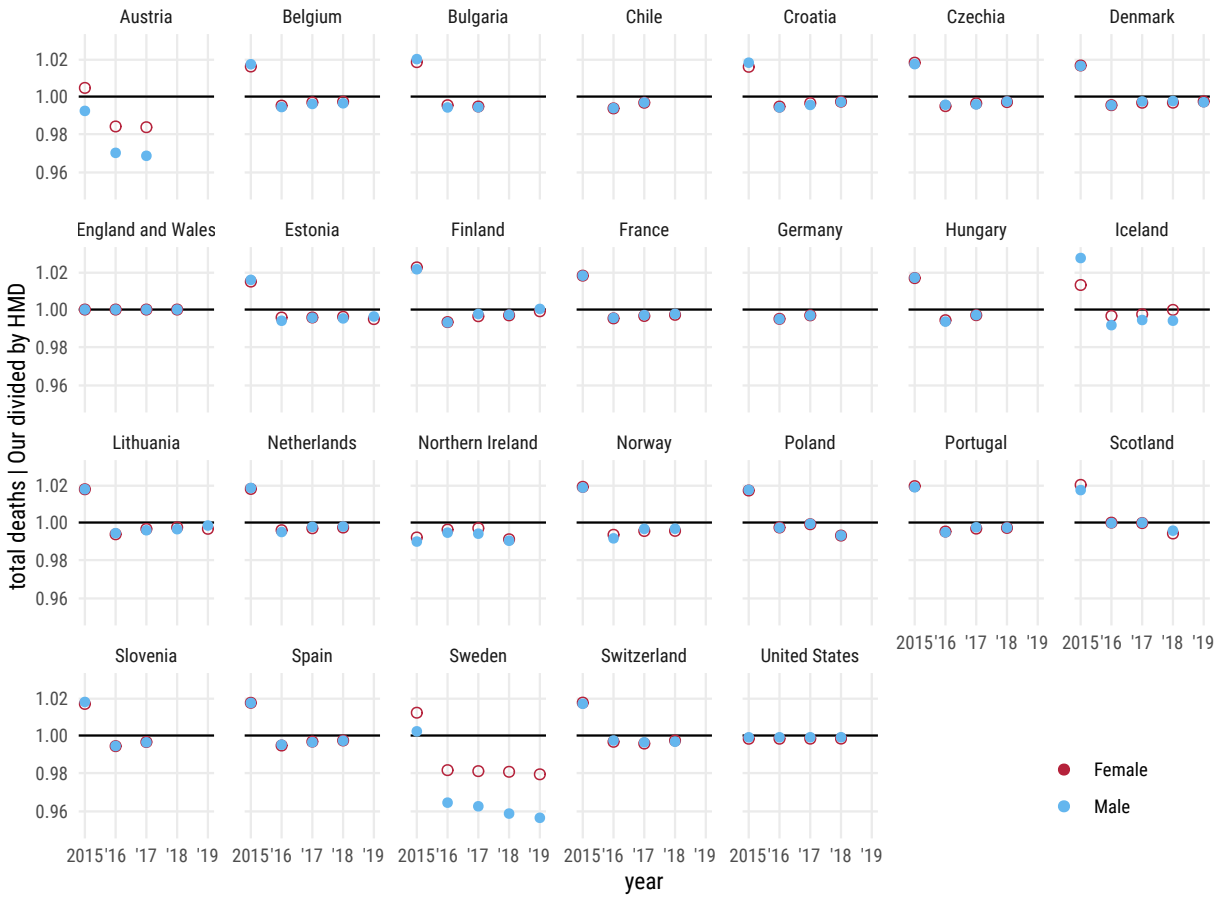

Figure S4: Comparison of death counts between the Short Term Mortality Fluctuations dataset and the Human Mortality Database.