

UCSF

UC San Francisco Previously Published Works

Title

Mapping 123 million neonatal, infant and child deaths between 2000 and 2017

Permalink

<https://escholarship.org/uc/item/6t93t1fk>

Journal

Nature, 574(7778)

ISSN

0028-0836

Authors

Burstein, Roy
Henry, Nathaniel J
Collison, Michael L
et al.

Publication Date

2019-10-01

DOI

10.1038/s41586-019-1545-0

Peer reviewed

Mapping 123 million neonatal, infant and child deaths between 2000 and 2017

A list of authors and their affiliations appears in the online version of the paper.

Since 2000, many countries have achieved considerable success in improving child survival, but localized progress remains unclear. To inform efforts towards United Nations Sustainable Development Goal 3.2—to end preventable child deaths by 2030—we need consistently estimated data at the subnational level regarding child mortality rates and trends. Here we quantified, for the period 2000–2017, the subnational variation in mortality rates and number of deaths of neonates, infants and children under 5 years of age within 99 low- and middle-income countries using a geostatistical survival model. We estimated that 32% of children under 5 in these countries lived in districts that had attained rates of 25 or fewer child deaths per 1,000 live births by 2017, and that 58% of child deaths between 2000 and 2017 in these countries could have been averted in the absence of geographical inequality. This study enables the identification of high-mortality clusters, patterns of progress and geographical inequalities to inform appropriate investments and implementations that will help to improve the health of all populations.

Gains in child survival have long served as an important proxy measure for improvements in overall population health and development^{1,2}. Global progress in reducing child deaths has been heralded as one of the greatest success stories of global health³. The annual global number of deaths of children under 5 years of age (under 5)⁴ has declined from 19.6 million in 1950 to 5.4 million in 2017. Nevertheless, these advances in child survival have been far from universally achieved, particularly in low- and middle-income countries (LMICs)⁴. Previous subnational child mortality assessments at the first (that is, states or provinces) or second (that is, districts or counties) administrative level indicate that extensive geographical inequalities persist^{5–7}.

Progress in child survival also diverges across age groups⁴. Global reductions in mortality rates of children under 5—that is, the under-5 mortality rate (U5MR)—among post-neonatal age groups are greater than those for mortality of neonates (0–28 days)^{4,8}. It is relatively unclear how these age patterns are shifting at a more local scale, posing challenges to ensuring child survival. To pursue the ambitious Sustainable Development Goal (SDG) of the United Nations⁹ to “end preventable deaths of newborns and children under 5” by 2030, it is vital for decision-makers at all levels to better understand where, and at what ages, child survival remains most tenuous.

Precision public health and child mortality

Country-level estimates facilitate international comparisons but mask important geographical heterogeneity. Previous assessments of mortality of children under 5 have noted significant within-country heterogeneity, particularly in sub-Saharan Africa^{5,7,10–14}, as well as in Brazil¹⁵, Iran¹⁶ and China¹⁷. Understanding public health risks at more granular subpopulation levels is central to the emerging concept of precision public health¹⁸, which uses “the best available data to target more effectively and efficiently interventions... to those most in need”¹⁸. Efforts to produce high-resolution estimates of mortality of children under 5, determinants at scales that cover the multiple countries are emerging, including for vaccine coverage^{19,20}, malaria²¹, diarrhoea²² and child growth failure^{23,24}. In a previous study, we produced comprehensive estimates of African child mortality rates at a 5 × 5-km scale for 5-year intervals⁵. For areas outside of Africa, in which 72% of the world’s children live and 46% of global child deaths occurred in 2017⁴, subnational heterogeneity remains mostly undescribed²⁵.

Here we produce estimates of death counts and mortality rates of children under 5, infants (under 1 years of age) and neonates (0–28 days)

in 99 countries at policy-relevant subnational scales (first and second administrative levels) for each year from 2000 to 2017. We fit a geostatistical discrete hazards model to a large dataset that is composed of 467 geo-referenced household surveys and censuses, representing approximately 15.9 million births and 1.1 million deaths of children from 2000 to 2017. Our model includes socioeconomic, environmental and health-related spatial covariates with known associations to child mortality and uses a Gaussian process random effect to exploit the correlation between data points near each other across dimensions of space, time and age group, which helps to mitigate the limitations associated with data sparsity in our estimations. For this study, we report U5MR as the expected number of deaths per 1,000 live births, reflecting the probability of dying before the age of 5 for a given location and year.

Unequal rates of child mortality

The risk of a newborn dying before their fifth birthday varies tremendously based on where in the world, and within their country, they are born. Across the 99 countries in this study, we estimate that U5MR varied as much as 24-fold at the national level in 2017, with the highest rate in the Central African Republic of 123.9 deaths (95% uncertainty interval, 104.9–148.2) per 1,000 live births, and the lowest rate in Cuba of 5.1 deaths (4.4–6.0)⁴. We observed large subnational variation within countries in which overall U5MR was either high or comparatively low. For example, in Vietnam, rates across second administrative units (henceforth referred to as ‘units’) varied 5.7-fold, from 6.9 (4.6–9.8) in the Tenth District in Hồ Chí Minh City to 39.7 (28.1–55.6) in Mường Tè District in the Northwest region (Figs. 1b, 2).

Decreases in U5MR between 2000 and 2017 were evident to some extent throughout all units (Figs. 1a, b, 2). No unit showed a significant increase in U5MR in this period, and in most units U5MR decreased greatly, even in units in which the mortality risk was the highest. Out of 17,554 units, 60.3% (10,585 units) showed a significant (defined as 95% uncertainty intervals that did not overlap) decrease in U5MR between 2000 and 2017. Across units in 2000, U5MR ranged from 7.5 (5.0–10.6) in Santa Clara district, Villa Clara province, Cuba, to 308.4 (274.9–348.4) in the Sabon Birni Local Government Area of Sokoto State, Nigeria. By 2017, the unit with the highest estimated U5MR across all 99 countries was Garki Local Government Area, Jigawa state, Nigeria, at 195.1 (158.6–230.9). Overall, the total percentage of units with a U5MR higher than 80 deaths per 1,000 live births decreased from 28.9% (5,070) of units in 2000 to 7.0% (1,236) in 2017. Furthermore,

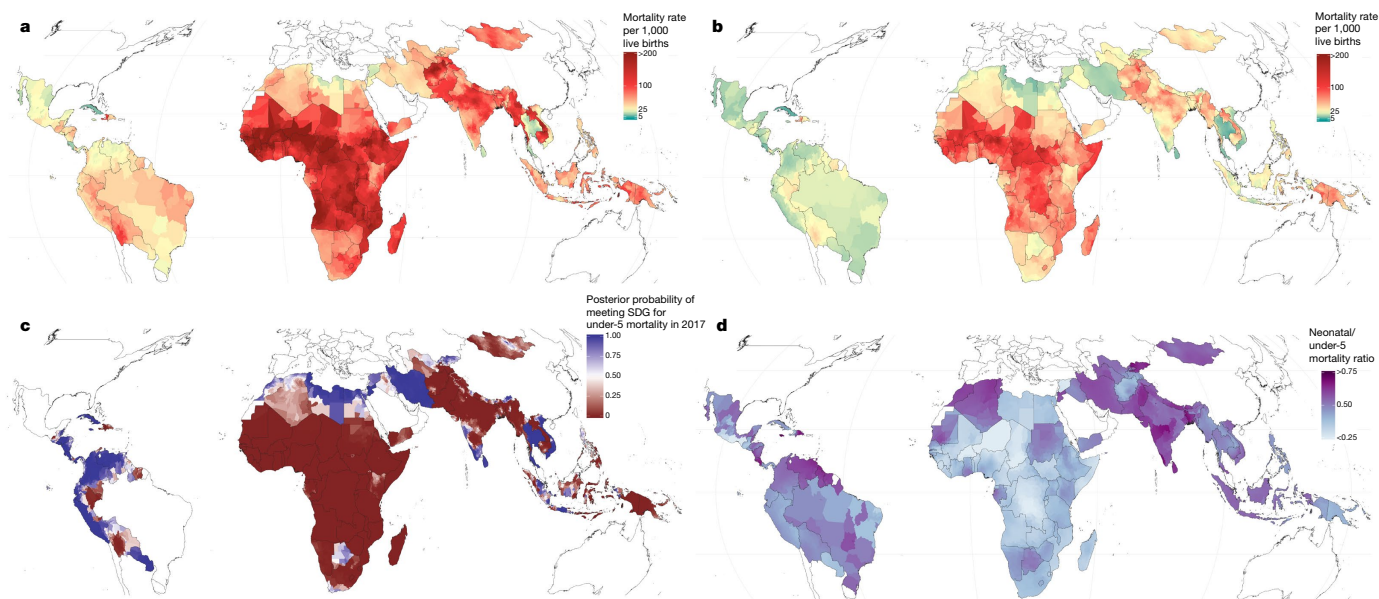


Fig. 1 | U5MR estimates in 99 LMICs. a, U5MR at the second administrative level in 2000. **b,** U5MR at the second administrative level in 2017. **c,** Modelled posterior exceedance probability that a given second administrative unit had achieved the SDG 3.2 target of 25 deaths per

1,000 live births for children under 5 in 2017. **d,** Proportion of mortality of children under 5 occurring in the neonatal (0–28 days) group at the second administrative level in 2017.

32% of units, representing 11.9% of the under-5 population in the 99 countries, had already met SDG 3.2 for U5MR with a 90% certainty threshold (Fig. 1c). For neonatal mortality, 34% of units met the target of ≤ 12 deaths per 1,000 live births (Extended Data Fig. 1). Within countries, successes were mixed in some cases. For example, Colombia, Guatemala, Libya, Panama, Peru and Vietnam had all achieved SDG 3.2 for U5MR at the national level by 2017, but each country had units that did not achieve the goal with 90% certainty (Fig. 1c).

Successful reductions in child mortality were also observed throughout entire countries. For example, in 43 LMICs across several world regions, the worst-performing unit in 2017 had a U5MR that was lower than the best-performing unit in 2000 (Fig. 2). Nearly half of these countries were in sub-Saharan Africa. Rwanda showed notable progress during the study period, reducing mortality from 144.0 (130.0–161.6) in its best-achieving district in 2000 (Rubavu) to 57.2 (47.4–72.1) in its worst-achieving district in 2017 (Kayanza). These broad reductions in U5MR have also led to a convergence of absolute subnational geographical inequalities, although relative subnational inequalities appear to be mostly unchanged between 2000 and 2017 (Fig. 2 and Supplementary Fig. 6.12). Despite this success, the highest U5MRs in 2017 were still largely concentrated in areas in which rates were highest in 2000 (Fig. 1a, b). We observed estimated U5MR ≥ 80 across large geographical areas in Western and Central sub-Saharan Africa, and within Afghanistan, Cambodia, Haiti, Laos and Myanmar (Fig. 1b).

Deaths of neonates (0–28 days of age) and post-neonates (28–364 days of age) have come to encompass a larger fraction of overall mortality of children under 5 in recent years. By 2017 (Fig. 1d), neonatal mortality increased as a proportion of total deaths of children under 5 in 91% (90) of countries and for 83% (14,656) of units compared to 2000. In almost all places where U5MR decreased, the share of the mortality burden increased in the groups of children with younger ages. Similarly, the mortality of infants (<1 year) has increased relative to the mortality for children who are 1–4 years of age in many areas. For example, in the Diourbel Region, Senegal, infant mortality constituted 54.4% (52.4–56.6) of total mortality of children under 5 in 2000; by 2017, the relative contribution of infant mortality was 73.2% (70.3–75.8). This shift towards mortality predominantly affecting neonates and infants was not as evident in all locations; mortality for children aged 1–4 years was responsible for more than 30% of overall under-5

deaths in 13% (2,226) of units, mostly within high-mortality areas in sub-Saharan Africa.

Distribution of under-5 deaths may not follow rates

The goal of mortality-reduction efforts is ultimately to prevent premature deaths, and not just to reduce mortality rates. Across the countries studied here, there were 3.5 million (41%) fewer deaths of children under 5 in 2017 than in 2000 (5.0 million compared to 8.5 million). At the national level, the largest number of child deaths in 2017 occurred in India (1.04 (0.98–1.10) million), Nigeria (0.79 (0.65–0.96) million), Pakistan (0.34 (0.27–0.41) million) and the Democratic Republic of the Congo (0.25 (0.21–0.31) million) (Fig. 3a). Within these countries, the geographical concentration of the deaths of the children varied. In Pakistan, over 50% of child deaths in 2017 occurred in Punjab province, which had a U5MR of 63.3 (54.1–76.0) deaths per 1,000 live births (Fig. 3b). By contrast, 50% of child deaths in the Democratic Republic of the Congo in 2017 occurred across 9 out of 26 provinces. Such findings are in a large part artefacts of how borders are drawn around various at-risk populations (the provinces above account for 53% and 63%, respectively, of the under-5 population that is at risk in these two countries), but can have a real impact at the level at which planning occurs. Some concentrated areas with apparent high absolute numbers of deaths highlighted by local-level estimates become less noticeable when reporting at aggregated administrative levels; for example, areas across Guatemala, Honduras and El Salvador are visually striking hot-spots in Fig. 3d, but less so in Fig. 3b, c.

Our estimates indicate that targeting areas with a ‘high’ U5MR of 80 will have a lower overall effect than in previous years owing to the reductions in mortality rates. In 2000, 23.7% of child deaths—representing 2.0 (1.7–2.4) million deaths—occurred in regions in which U5MR was less than 80 that year (Fig. 4). By comparison, in 2017, 69.5% of child deaths occurred in areas in which U5MR was below 80. A growing proportion of deaths of children under 5 are occurring in ‘low’-mortality areas; 7.3% (5.1–10.2) of all deaths of children under 5 in 2017 occurred in locations in which the U5MR was below the SDG 3.2 target rate of 25, compared to 1.2% (0.9–1.6) in 2000. For instance, Lima, Peru, has a U5MR in the 8th percentile of units in this study, yet it ranks in the 96th percentile of highest number of deaths of children under 5.

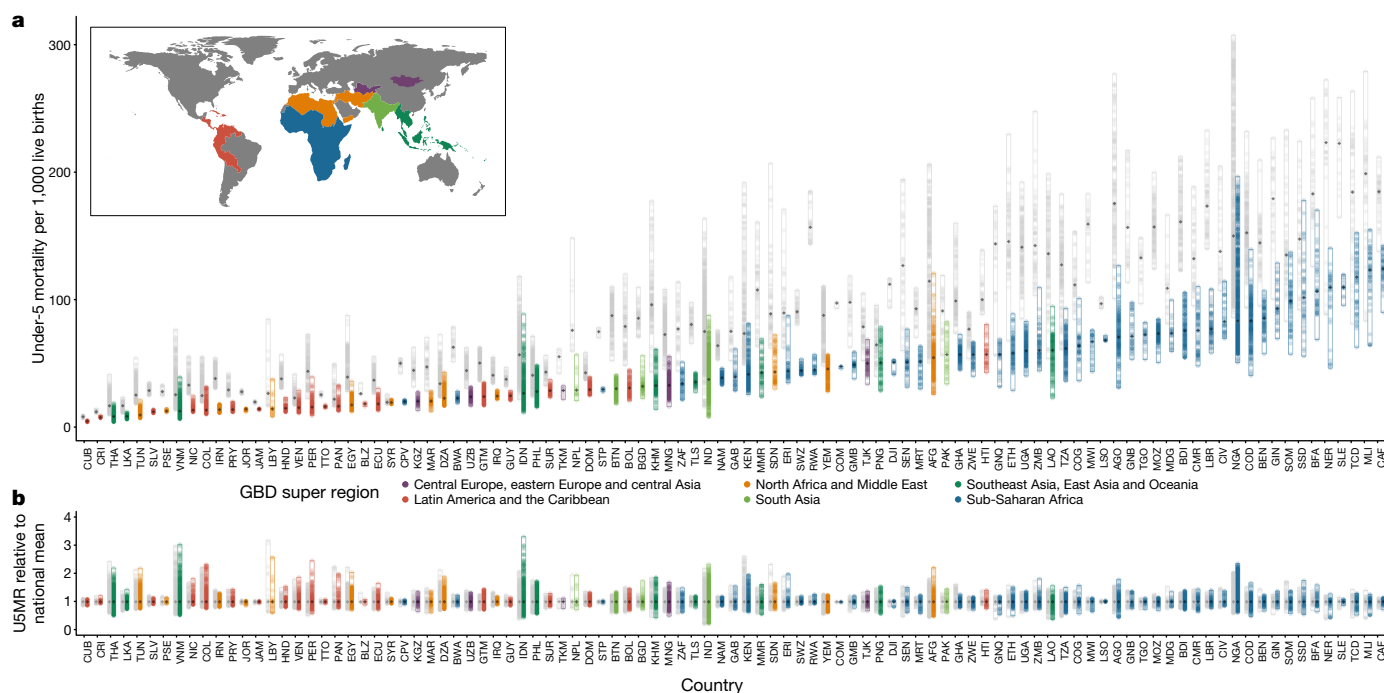


Fig. 2 | Geographical inequality in U5MR across 99 countries for 2000 and 2017. **a**, Absolute inequalities. Range of U5MR estimates in second administrative-level units across 99 LMICs. **b**, Relative inequalities. Range of ratios of U5MR estimates in second administrative-level units relative to country means. Each dot represents a second administrative-level unit. The lower bound of each bar represents the second administrative-level unit with the lowest U5MR in each country. The upper end of each bar represents the second administrative-level unit with the highest U5MR

in each country. Thus, each bar represents the extent of geographical inequality in U5MRs estimated for each country. Bars indicating the range in 2017 are coloured according to their Global Burden of Disease super-region. Grey bars indicate the range in U5MR in 2000. The diamond in each bar represents the median U5MR estimated across second administrative-level units in each country and year. A coloured bar that is shorter than its grey counterpart indicates that geographical inequality has narrowed.

Despite population growth, child deaths have declined due to the outpaced decline in U5MR. For example, there were a total of 8.5 (7.2–10.0) million deaths of children under 5 in the countries in this study in 2000; had the 2017 under-5 population been exposed to the same U5MRs that were observed in 2000, there would have been 10.6 (9.0–12.5) million deaths in 2017. Instead, we observed 5.0 (3.8–6.6) million deaths in 2017 (Extended Data Fig. 5).

Finally, we combine estimates of subnational variation in mortality rates and populations to gain a better understanding of the impact of geographical inequality. Overall, 2.7 (2.5–2.9) million deaths, or 54% of the total number of deaths of children under 5, would have been averted in 2017 had all units had a U5MR that matched the best-performing unit in each respective country (Extended Data Fig. 2). Over the 2000–2017 period, this number is 71.8 (68.5–74.9) million deaths, or 58% (55–61) of the total number of deaths of children under 5. Total deaths attributable to inequality in this scenario ranged from 13 (6–24) deaths in Belize to 0.84 (0.72–0.99) million deaths in India. Furthermore, had all units met the SDG 3.2 target of 25 deaths per 1,000, an estimated 2.6 (2.3–2.8) million deaths of children under 5 would have been averted in 2017.

Discussion

This study offers a comprehensive, geospatially resolved resource for national and subnational estimates of child deaths and mortality rates for 99 LMICs, where 93% of the world's child deaths⁴ occurred in 2017. Gains in child survival varied substantially within the vast majority of countries from 2000 to 2017. Countries such as Vietnam, for example, showed more than fivefold variation in mortality rates across second administrative-level units. The inconsistency of successes, even at subnational levels, indicates how differences in health policy, financial resources, access to and use of health services, infrastructure, and economic development ultimately contribute to millions of lives cut short^{25–27}. By providing detailed maps that show precisely where these

deaths are estimated to have occurred, we provide an important evidence base for looking both to the past, for examples of success, and towards the future, in order to identify where precision public-health initiatives could save the most lives.

The epidemiological toll of child mortality should be considered both in terms of total deaths and as rates of mortality. Focusing only on mortality rates can effectively mask areas in which rates are comparatively low but child deaths are high owing to large population sizes. The number of deaths that occur in high-risk areas has declined, and most under-5 deaths in recent years have occurred in lower-risk areas. This 'prevention paradox'²⁸ could indicate that whole-population interventions could have a larger overall impact than targeting high-risk areas²⁹. At the same time, strategies that target resources to those locations that have the highest number of child deaths risk leaving behind some of the world's most marginalized communities: remote, more-sparsely populated places in which, relative to the number of children born each year, a large number of children die before their fifth birthday. Instead, by considering subnational measures of both counts and rates of deaths of children under 5, decision-makers can better tailor child health programs to align with local contexts, norms and needs. Rural communities with high rates but low counts may benefit from 'last-mile' initiatives to provide effective health services to populations who lack adequate access to care. By contrast, locations with low rates but high counts may require programs that focus on alleviating the cost of care, unsafe environmental exposures or health risks that are uniquely associated with urban slums³⁰. The SDGs have pointed the global development agenda towards progress in child survival. Our analysis indicates that reaching the SDG 3.2 targets of 25 child deaths per 1,000 live births and 12 neonatal deaths per 1,000 live births will require only modest improvements or have already been achieved by some units; however, these targets are ambitious for other units in which child mortality remains high. It is worth noting that many countries contain areas that fit both of these profiles. For example, 11 countries

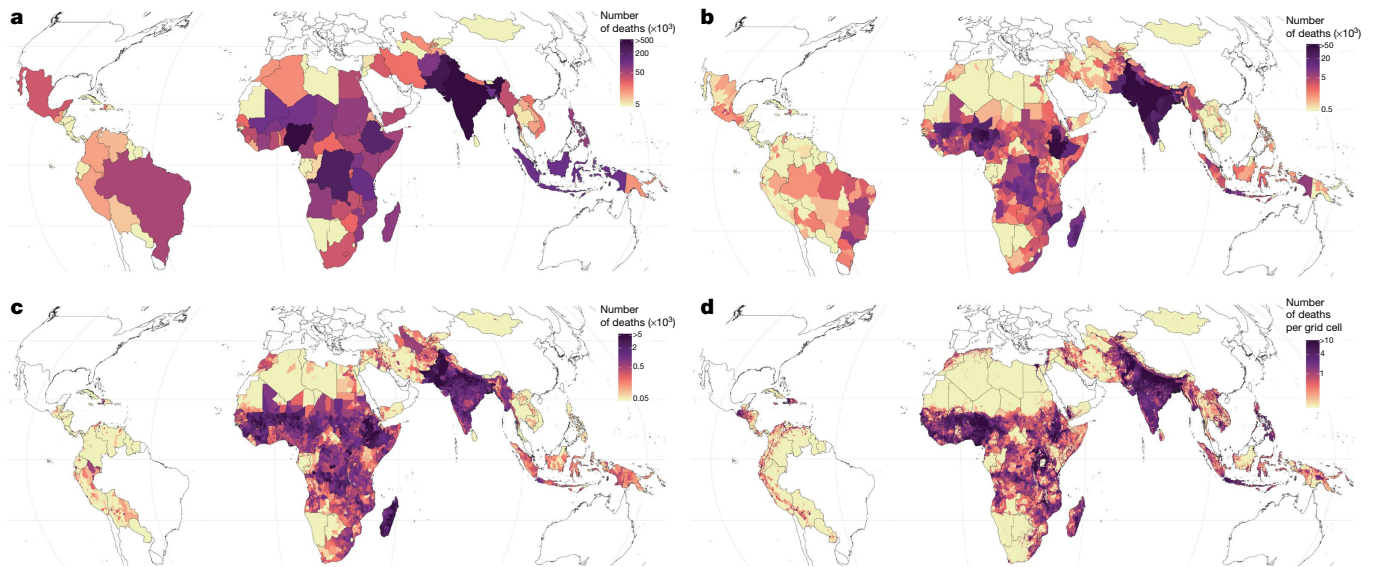


Fig. 3 | Estimated number of children under 5 who died within 99 countries in 2017. a, Number of deaths of children under 5 in each country. **b,** Number of deaths in each first administrative-level unit.

c, Number of deaths in each second administrative-level unit. **d,** Number of deaths of children under 5 in each 5×5 -km grid cell. Note that scales vary for each aggregation unit.

had at least 1 unit that had already met SDG 3.2 with high certainty, and at least 1 unit that had not. Subnational estimates can empower countries to benchmark gains in child survival against their own subnational exemplars as well as advances that have been achieved by their peers. Through our counterfactual analysis we showed that even if all units had met the SDG 3.2 goal in 2017, there would still have been 2.4 million deaths of children under 5, indicating that ‘ending preventable child deaths’ is more complex than simply meeting a target threshold. Future research efforts must address the causes of child mortality in local areas and more precisely identify causes of child deaths that are amenable to intervention. To that end, new and innovative data-collection efforts, such as the ongoing Child Health and Mortality Prevention Surveillance network, offer promising prospects by applying high-validity, pathology-based methods alongside verbal autopsies to determine the cause of death³¹.

This study offers a unique platform to support the identification of local success stories that could be replicated elsewhere. In Rwanda, for example, the highest U5MR at the district level in 2017 was 60.2% (52.0–67.8%) lower than the lowest U5MR at the district level in 2000. Such gains have been partially credited to focused investments in the country’s poorest populations, expanding the Mutuelles de santé insurance program, and developing a strong workforce of community health workers who provide evidence-based treatment and health promotion^{32,33}. Nepal and Cambodia are among the exemplars for considerably decreasing subnational inequalities in child survival since 2000. In an era when narrowing disparities within countries is as important as reducing national-level gaps, these results provide the evidence base to inform best practices and stimulate national conversations about related social determinants.

Neonatal mortality rates have also declined but failed to keep pace with reductions in mortality rates of older children, leading to a higher proportion of deaths of children under 5 occurring within the first four weeks of life: from 37.4% (37.1–37.7) in 2000 to 43.7% (43.1–44.3%) in 2017. This trend is probably related to the increase in scale of routine programs and improved infrastructure (for example, vaccination³⁴, and water and sanitation³⁵) and the introduction of effective interventions to target communicable diseases (for example, malaria control³⁶ and prevention of mother-to-child transmission of HIV³⁷). These interventions have tended to target amenable causes of mortality that are more common in older children under 5 rather than dominant causes of neonatal mortality, such as prematurity and congenital anomalies³⁸.

Notably, irrespective of income level or location, some causes of neonatal death (for example, chromosomal anomalies and severe preterm birth complications) remain difficult to prevent completely with current medical technologies. Ultimately, large gains in neonatal mortality will require serious investment in health system strengthening³⁹. Affordable approaches to preventing the majority of neonatal deaths in LMICs exist and there are success stories with lessons learned to apply^{40–44}, but decisions about which approaches to take must be based on the local epidemiological and health system context. In the absence of spatially detailed cause of death data, subnational neonatal mortality estimates can indicate dominant causes and thus serve as a useful proxy to guide prioritization of interventions⁴⁵.

The accuracy and precision of our estimates were primarily determined by the timeliness, quantity and quality of available data. In Sri Lanka, for example, there were no available surveys, and the wide uncertainty intervals surrounding estimates reflect the dearth of available evidence in that country (Extended Data Figs. 3, 4). In certain areas, this decreased the confidence that we had in claiming that a specific subnational area met the SDG 3.2 target (Fig. 1c). This issue is most concerning in cases in which estimated mortality rates are high, thus helping to identify locations in which it would be most useful to focus future data-collection efforts. High mortality rates with large uncertainty intervals were estimated across much of Eastern and Central sub-Saharan Africa, and in Cambodia, Laos, Myanmar and Papua New Guinea (Extended Data Figs. 3, 4). Furthermore, ongoing conflict in countries such as Syria, Yemen and Iraq pose substantial challenges to collecting more contemporaneous data, and our estimates may not fully capture the effects of prolonged civil unrest or war^{46,47}. Further methodological and data limitations are discussed in the Methods.

The accurate estimation of mortality is also a matter of equity; highly refined health surveillance is common in high-income countries, whereas in LMICs, in which rates of child mortality are the highest, surveillance that helps to guide investments in health towards the areas with the greatest need is less routine⁴⁸. Ideally, all countries would have high-quality, continuous, and complete civil and vital registration systems that capture all of the births, deaths and causes of death at the appropriate geographical resolution⁴⁹. In the meantime, analyses such as this serve to bridge the information gap that exists between low-mortality countries with strong information systems and countries that face a dual challenge of weaker information systems and higher disease burden.

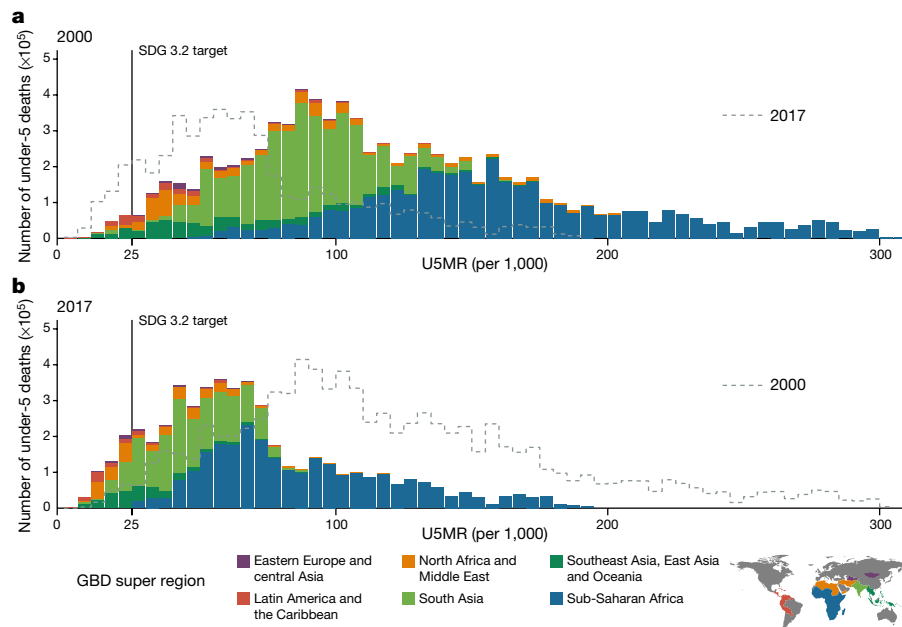


Fig. 4 | Number of deaths of children under 5, distributed across level of U5MR, in 2000 and in 2017, across 99 countries. Bar heights represent the total number of deaths of children under 5 within all second administrative-level units with corresponding U5MR. Bins are a width of 5 deaths per 1,000 live births. The colour of each bar represents the global region as defined by the subset legend map. As such, the sum of heights

of all bars represents the total number of deaths across the 99 countries. **a**, Deaths of children under 5 in 2000. **b**, Deaths of children under 5 in 2017. The dotted line in the 2000 plot is the shape of the distribution in 2017, and the dotted line in the 2017 plot represents the distribution in 2000.

By harnessing the unprecedented availability of geo-referenced data and developing robust statistical methods, we provide a high-resolution atlas of child death counts and rates since 2000, covering countries that account for 93% of child deaths. We bring attention to subnational geographical inequalities in the distribution, rates and absolute counts of child deaths by age. These high-resolution estimates can help decision-makers to structure policy and program implementation and facilitate pathways to end preventable child deaths⁵⁰ by 2030.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at <https://doi.org/10.1038/s41586-019-1545-0>.

Received: 28 March 2019; Accepted: 6 August 2019;
Published online 16 October 2019.

- Reidpath, D. D. & Allotey, P. Infant mortality rate as an indicator of population health. *J. Epidemiol. Community Health* **57**, 344–346 (2003).
- United Nations General Assembly. *United Nations Millennium Declaration: Resolution adopted by the General Assembly. A/RES/55/2* (UN General Assembly, 2000).
- Centers for Disease Control and Prevention. *Ten Great Public Health Achievements—Worldwide, 2001–2010*. <https://www.cdc.gov/mmwr/preview/mmwrhtml/mm6024a4.htm> (2011).
- GBD 2017 Mortality Collaborators. Global, regional, and national age-sex-specific mortality and life expectancy, 1950–2017: a systematic analysis for the Global Burden of Disease Study 2017. *Lancet* **392**, 1684–1735 (2018).
- Golding, N. et al. Mapping under-5 and neonatal mortality in Africa, 2000–15: a baseline analysis for the Sustainable Development Goals. *Lancet* **390**, 2171–2182 (2017).
- Pezzulo, C. et al. *Geospatial Modeling of Child Mortality across 27 Countries in sub-Saharan Africa. DHS Spatial Analysis Reports No. 13* (USAID, 2016).
- Li, Z. et al. Changes in the spatial distribution of the under-five mortality rate: small-area analysis of 122 DHS surveys in 262 subregions of 35 countries in Africa. *PLoS ONE* **14**, e0210645 (2019).
- Lawn, J. E., Cousens, S. & Zupan, J. 4 million neonatal deaths: When? Where? Why? *Lancet* **365**, 891–900 (2005).
- World Health Organization. *SDG 3: Ensure healthy lives and promote wellbeing for all at all ages*. <https://www.who.int/sdg/targets/en/> (2019).
- Dwyer-Lindgren, L. et al. Estimation of district-level under-5 mortality in Zambia using birth history data, 1980–2010. *Spat. Spatio-temporal Epidemiol.* **11**, 89–107 (2014).

- Dwyer-Lindgren, L. et al. Small area estimation of under-5 mortality in Bangladesh, Cameroon, Chad, Mozambique, Uganda, and Zambia using spatially misaligned data. *Popul. Health Metr.* **16**, 13 (2018).
- Wakefield, J. et al. Estimating under-five mortality in space and time in a developing world context. *Stat. Methods Med. Res.* <https://doi.org/10.1177/0962280218767988> (2018).
- Burke, M., Heft-Neal, S. & Bendavid, E. Sources of variation in under-5 mortality across sub-Saharan Africa: a spatial analysis. *Lancet Glob. Health* **4**, e936–e945 (2016).
- Macharia, P. M. et al. Sub national variation and inequalities in under-five mortality in Kenya since 1965. *BMC Public Health* **19**, 146 (2019).
- Sousa, A., Hill, K. & Dal Poz, M. R. Sub-national assessment of inequality trends in neonatal and child mortality in Brazil. *Int. J. Equity Health* **9**, 21 (2010).
- Mohammadi, Y. et al. Measuring Iran's success in achieving Millennium Development Goal 4: a systematic analysis of under-5 mortality at national and subnational levels from 1990 to 2015. *Lancet Glob. Health* **5**, e537–e544 (2017).
- Wang, Y. et al. Under-5 mortality in 2851 Chinese counties, 1996–2012: a subnational assessment of achieving MDG 4 goals in China. *Lancet* **387**, 273–283 (2016).
- Horton, R. Offline: in defence of precision public health. *Lancet* **392**, 1504 (2018).
- Takahashi, S., Metcalf, C. J. E., Ferrari, M. J., Tatem, A. J. & Lessler, J. The geography of measles vaccination in the African Great Lakes region. *Nat. Commun.* **8**, 15585 (2017).
- Utazi, C. E. et al. High resolution age-structured mapping of childhood vaccination coverage in low and middle income countries. *Vaccine* **36**, 1583–1591 (2018).
- Gething, P. W. et al. Mapping *Plasmodium falciparum* mortality in Africa between 1990 and 2015. *N. Engl. J. Med.* **375**, 2435–2445 (2016).
- Reiner, R. C. Jr et al. Variation in childhood diarrhoeal morbidity and mortality in Africa, 2000–2015. *N. Engl. J. Med.* **379**, 1128–1138 (2018).
- Osgood-Zimmerman, A. et al. Mapping child growth failure in Africa between 2000 and 2015. *Nature* **555**, 41–47 (2018).
- Amoah, B., Giorgi, E., Heyes, D. J., van Buren, S. & Diggle, P. J. Geostatistical modelling of the association between malaria and child growth in Africa. *Int. J. Health Geogr.* **17**, 7 (2018).
- Bishai, D. M. et al. Factors contributing to maternal and child mortality reductions in 146 low- and middle-income countries between 1990 and 2010. *PLoS ONE* **11**, e0144908 (2016).
- Marmot, M. Social determinants of health inequalities. *Lancet* **365**, 1099–1104 (2005).
- Victora, C. G. et al. Countdown to 2015: a decade of tracking progress for maternal, newborn, and child survival. *Lancet* **387**, 2049–2059 (2016).
- Rose, G. Strategy of prevention: lessons from cardiovascular disease. *Br. Med. J. (Clin. Res. Ed.)* **282**, 1847–1851 (1981).
- Mackenbach, J. P., Lingsma, H. F., van Ravesteyn, N. T. & Kamphuis, C. B. M. The population and high-risk approaches to prevention: quantitative estimates of their contribution to population health in the Netherlands, 1970–2010. *Eur. J. Public Health* **23**, 909–915 (2013).

30. Agarwal, S. & Taneja, S. All slums are not equal: child health conditions among the urban poor. *Indian Pediatr.* **42**, 233–244 (2005).
31. Farag, T. H. et al. Precisely tracking childhood death. *Am. J. Trop. Med. Hyg.* **97**, 3–5 (2017).
32. Farmer, P. E. et al. Reduced premature mortality in Rwanda: lessons from success. *Br. Med. J.* **346**, f65 (2013).
33. Gurusamy, P. S. R. & Janagaraj, P. D. A success story: the burden of maternal, neonatal and childhood mortality in Rwanda - critical appraisal of interventions and recommendations for the future. *Afr. J. Reprod. Health* **22**, 9–16 (2018).
34. McGovern, M. E. & Canning, D. Vaccination and all-cause child mortality from 1985 to 2011: global evidence from the Demographic and Health Surveys. *Am. J. Epidemiol.* **182**, 791–798 (2015).
35. Cheng, J. J., Schuster-Wallace, C. J., Watt, S., Newbold, B. K. & Mente, A. An ecological quantification of the relationships between water, sanitation and infant, child, and maternal mortality. *Environ. Health* **11**, 4 (2012).
36. Steketee, R. W. & Campbell, C. C. Impact of national malaria control scale-up programmes in Africa: magnitude and attribution of effects. *Malar. J.* **9**, 299 (2010).
37. Kiragu, K., Collins, L., Von Zinkernagel, D. & Mushavi, A. Integrating PMTCT into maternal, newborn, and child health and related services: experiences from the global plan priority countries. *J. Acquir. Immune Defic. Syndr.* **75**, S36–S42 (2017).
38. GBD 2017 Causes of Death Collaborators. Global, regional, and national age-sex-specific mortality for 282 causes of death in 195 countries and territories, 1980–2017: a systematic analysis for the Global Burden of Disease Study 2017. *Lancet* **392**, 1736–1788 (2018).
39. Pasha, O. et al. A combined community- and facility-based approach to improve pregnancy outcomes in low-resource settings: a Global Network cluster randomized trial. *BMC Med.* **11**, 215 (2013).
40. Horton, S. et al. Ranking 93 health interventions for low- and middle-income countries by cost-effectiveness. *PLoS ONE* **12**, e0182951 (2017).
41. Simmons, L. E., Rubens, C. E., Darmstadt, G. L. & Gravett, M. G. Preventing preterm birth and neonatal mortality: exploring the epidemiology, causes, and interventions. *Semin. Perinatol.* **34**, 408–415 (2010).
42. Darmstadt, G. L. et al. Evidence-based, cost-effective interventions: how many newborn babies can we save? *Lancet* **365**, 977–988 (2005).
43. Saugstad, O. D. Reducing global neonatal mortality is possible. *Neonatology* **99**, 250–257 (2011).
44. Ntigurirwa, P. et al. A health partnership to reduce neonatal mortality in four hospitals in Rwanda. *Glob. Health* **13**, 28 (2017).
45. Knippenberg, R. et al. Systematic scaling up of neonatal care in countries. *Lancet* **365**, 1087–1098 (2005).
46. GBD 2015 Eastern Mediterranean Region Neonatal, Infant, and under-5 Mortality Collaborators. Neonatal, infant, and under-5 mortality and morbidity burden in the Eastern Mediterranean region: findings from the Global Burden of Disease 2015 study. *Int. J. Public Health* **63**, 63–77 (2018).
47. Wagner, Z. et al. Armed conflict and child mortality in Africa: a geospatial analysis. *Lancet* **392**, 857–865 (2018).
48. Mikkelsen, L. et al. A global assessment of civil registration and vital statistics systems: monitoring data quality and progress. *Lancet* **386**, 1395–1406 (2015).
49. AbouZahr, C. et al. Civil registration and vital statistics: progress in the data revolution for counting and accountability. *Lancet* **386**, 1373–1385 (2015).
50. Annan, K. Data can help to end malnutrition across Africa. *Nature* **555**, 7 (2018).

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit <http://creativecommons.org/licenses/by/4.0/>.

© The Author(s) 2019

- Roy Burstein^{1,612}, Nathaniel J. Henry^{1,612}, Michael L. Collison¹, Laurie B. Marczak¹, Amber Sligar¹, Stefanie Watson¹, Neal Marquez¹, Mahdieh Abbasalizad-Farhang², Masoumeh Abbasi³, Foad Abd-Allah⁴, Amir Abdoli⁵, Mohammad Abdollahi⁶, Ibrahim Abdollahpour^{7,8}, Rizwan Sullankatchi Abdulkader⁹, Michael R. M. Abrigo¹⁰, Dilaram Acharya^{11,12}, Oladimeji M. Adebayo¹³, Victor Adekanmbi¹⁴, Davoud Adham¹⁵, Mahdi Afshari¹⁶, Mohammad Aghaali¹⁷, Keivan Ahmadi¹⁸, Mehdi Ahmadi¹⁹, Ehsan Ahmadvand²⁰, Rushdia Ahmed^{21,22}, Chalachev Genet Akal²³, Joshua A. Akinyemi²⁴, Fahs Alahad²⁵, Noore Alam²⁶, Genet Melak Alamene²⁷, Keyalew Addis Alene^{28,29}, Mehran Alijanzadeh³⁰, Cyrus Alinia³¹, Vahid Alipour^{32,33}, Syed Mohamed Aljunid^{34,35}, Mohammed J. Almkali^{36,37}, Hesham M. Al-Mekhlafi^{38,39}, Khalid Altirkawi⁴⁰, Nelson Alvis-Guzman^{41,42}, Adeladza Kofi Amegah⁴³, Saeed Amini⁴⁴, Arianna Maever Loreche Amit^{45,46}, Zohreh Anbari⁴⁷, Sofia Androudi⁴⁷, Mina Anjomshoa⁴⁸, Fereshteh Ansari⁴⁹, Carl Abelardo T. Antonio^{50,51}, Jalal Arabloo³³, Zohreh Arefi⁵², Olatunde Aremu⁵³, Bahram Armoon^{54,55}, Amit Arora^{56,57}, Al Artaman⁵⁸, Anvar Asadi⁵⁹, Mehran Asadi-Aliabadi⁶⁰, Amir Ashraf-Ganjouei^{7,61}, Reza Assadi⁶², Bahar Ateinia⁶³, Sachin R. Atrhe^{64,65}, Beatriz Paulina Ayala Quintanilla^{66,67}, Martin Amogre Ayanore⁶⁸, Samad Azari³³, Ebrahim Babaei⁶⁰, Arefeh Babazadeh⁶⁹, Alaa Badawi^{70,71}, Soghra Bagheri³, Mojtaba Bagherzadeh⁷², Nafiseh Baheiraee^{73,74}, Abbas Balouchi⁷⁵, Aleksandra Barac^{76,77}, Quique Bassat^{78,79}, Bernhard T. Baume⁸⁰, Mohsen Bayati⁸¹, Neeraj Bedi^{37,82}, Ettore Beghi⁸³, Masoud Behzadifar⁸⁴, Meysam Behzadifar⁸⁵, Yared Belete Belay⁸⁶, Brent Bell¹, Michelle L. Bell⁸⁷, Dessalegn Ajema Berbada⁸⁸, Robert S. Bernstein^{89,90}, Natalia V. Bhattacharjee¹, Suraj Bhattarai^{91,92}, Zulfiqar A. Bhutta^{93,94}, Ali Bijani⁹⁵, Somayeh Bohlooli⁹⁶, Nicholas J. K. Breitborde^{97,98}, Gabrielle Britton^{99,100}, Annie J. Browne¹⁰¹, Sharath Burugina Nagaraja¹⁰², Reinhard Busse¹⁰³, Zahid A. Butt^{104,105}, Josip Car^{106,107}, Rosario Cárdenas¹⁰⁸, Carlos A. Castañeda-Orjuela^{109,110}, Ester Cerin^{111,112}, Wagaye Fentahun Chanie¹¹³, Pranab Chatterjee¹¹⁴, Dinh-Toi Chu¹¹⁵, Cyrus Cooper^{116,117}, Vera M. Costa¹¹⁸, Koustuv Dalai^{119,120}, Lalit Dandona¹²¹, Rakhi Dandona¹²¹, Farah Daoud¹, Ahmad Daryani¹²², Rajat Das Gupta², Ian Davis¹, Nicole Davis Weaver¹, Dragos Virgil Davitov^{123,124}, Jan-Walter De Neve¹²⁵, Feleke Mekonnen Demekle¹²⁶, Gebre Teklemariam Demoz^{127,128}, Kebede Deribe^{129,130}, Rupak Desai¹³¹, Aniruddha Deshpande¹³¹, Hanna Demelash Desyibelev¹³², Sagnik Dey¹³³, Samath Dhamminda Dharmaratne¹³⁴, Meghnath Dhimal¹³⁵, Daniel Diaz^{136,137}, Leila Doshmangir¹³⁸, Andre R. Duraes^{139,140}, Laura Dwyer-Lindgren¹⁴¹, Lucas Earl¹, Roya Ebrahim¹⁴², Soheil Ebrahimpour⁶⁹, Andem Effiong¹⁴³, Aziz Eftekhari^{144,145}, Elham Ehsani-Chimeh¹⁴⁶, Iman El Sayed¹⁴⁷, Maysaa El Sayed Zaki¹⁴⁸, Maha El Tantawi^{149,150}, Ziad El-Khatib¹⁵¹, Mohammad Hassan Emamian¹⁵², Shymaa Enay¹⁵³, Sharareh Eskandarieh⁷, Oghenowede Eyawo^{154,155}, Maha Ezalarab¹, Mahbobeh Faramarz¹⁵⁶, Mohammad Fareed¹⁵⁷, Roghiyeh Faridnia¹⁵⁸, Andre Faro¹⁵⁹, Ali Akbar Fazaeli¹⁶⁰, Mehdi Fazlzadeh^{161,162}, Netsanet Fentahun¹⁶³, Seyed-Mohammad Fereshtehnejad^{164,165}, João C. Fernandes¹⁶⁶, Irina Filip^{167,168}, Florian Fischer¹⁶⁹, Nataliya A. Foigt¹⁷⁰, Masoud Forouzan¹⁷¹, Joel Msafiri Francis¹⁷², Takeshi Fukumoto^{173,174}, Nancy Fullman¹, Silvano Gallus¹⁷⁵, Destallem Gebremedhin Gebre^{176,177}, Tsegaye Tewelde Gebrehiwot¹⁷⁸, Gebremiaki Gebremedhin Gebremeskel^{179,180}, Bradford D. Gessner^{181,182}, Birhanu Geta¹⁸³, Peter W. Gething¹⁰¹, Reza Ghadimi¹⁸⁴, Keyghobad Ghadiri³, Mahsa Ghajarzadeh¹⁸⁵, Ahmad Ghashghaie¹⁸⁶, Paramjit Singh Gill¹⁸⁷, Tiffany K. Gill¹⁸⁸, Nick Golding⁶⁹, Nelson G. M. Gomes^{189,190}, Philimon N. Gona¹⁹¹, Sameer Vali Gopalan^{192,193}, Giuseppe Gorini¹⁹⁴, Bárbara Niegia Garcia Goulart¹⁹⁵, Nicholas Graetz¹, Felix Greaves^{196,197}, Manfred S. Green¹⁹⁸, Yuming Guo^{199,200}, Arvin Haj-Mirzaian^{201,202}, Arya Haj-Mirzaian^{201,203}, Brian James Hall²⁰⁴, Sameer Hamidi²⁰⁵, Amir Hashem Hariri²⁰⁶, Josep Maria Haro^{207,208}, Samed Hasankhani²⁰⁹, Edris Hasanpoor²¹⁰, Amir Hasanzadeh^{211,212}, Hadi Hassankhani^{213,214}, Hamid Yimam Hassen^{215,216}, Mohamed I. Hegazy¹, Delia Hendrie²¹⁷, Fatemeh Heydarpour²¹⁸, Thomas R. Hird^{199,219}, Chi Linh Hoang²²⁰, Gillian Hollerich¹, Enayatollah Homaie Rad^{221,222}, Mojtaba Hoseini-Ghahfarokhi²²³, Naznin Hossain^{224,224}, Mostafa Hosseini²²⁵, Mehdi Hosseinzadeh^{33,226}, Mihaela Hostiuc^{123,227}, Sorin Hostiuc^{228,229}, Mowafa Househ^{230,231}, Mohamed Hsairi²³², Olayinka Stephen Ilesanmi²³³, Mohammad Hasan Imani-Nasab²³⁴, Usman Iqbal²³⁵, Seyed Sina Naghibi Irvani²³⁶, Nazrul Islam^{237,238}, Sheikh Mohammed Shariful Islam^{239,240}, Mikko Jürisson²⁴¹, Nader Jafari Balalami²⁴², Amir Jalali²⁴³, Javad Javidnia²⁴⁴, Achala Upendra Jayatilake^{245,246}, Ensiyeh Jenabi²⁴⁷, John S. J. 248, Yash B. Jobanputra²⁴⁹, Kimberly Johnson¹, Jost B. Jonas^{250,251}, Zahra Jorjoran Shushitari²⁵², Jacek Jerzy Jozwiak^{253,254}, Ali Kabir²⁵⁵, Amaha Kasty²⁵⁶, Hamed Kalani^{257,258}, Rohollah Kalhor²⁵⁹, Manoochehr Karami²⁶⁰, Surendra Karik^{261,262}, Amir Kaseaie^{263,264}, Nicholas J. Kassebaum^{1,265}, Peter Njenga Keiyoro²⁶⁶, Grant Rodgers Kemp^{1,267}, Roghayeh Khabiri^{268,269}, Yousef Saleh Khader²⁷⁰, Morteza Abdullatif Khataie²⁷¹, Ejaz Ahmad Khan²⁷², Junaid Khan²⁷³, Muhammad Shahzeb Khan^{274,275}, Young-Ho Khang^{276,277}, Khaled Khatib^{278,279}, Amir Khater²⁸⁰, Mona M. Khater²⁸¹, Alireza Khatony³, Mohammad Khazaei²⁸², Salman Khazaei²⁶⁰, Maryam Khazaei-Pool²⁸³, Jagdish Khubchandani²⁸⁴, Neda Kianipour^{3,285}, Yun Jin Kim²⁸⁶, Ruth W. Kimokoti²⁸⁷, Damaris K. Kinyoki^{1,141}, Adnan Kisa^{288,289}, Sezer Kisa²⁹⁰, Tufa Kolola²⁹¹, Soewarta Kosen²⁹², Parvaiz A. Koul²⁹³, Ai Koyanagi^{294,294}, Moritz U. G. Kraemer^{295,296}, Kewal Krishan²⁹⁷, Kris J. Krohn¹, Nurwora Kugbey^{298,299}, G. Anil Kumar¹²¹, Manasi Kumar^{300,301}, Pushpendra Kumar³⁰², Desmond Kuupiel^{303,304}, Ben Lacey^{305,306}, Sheetal D. Lad³⁰⁷, Faris Hasan Lami³⁰⁸, Anders O. Larsson^{309,310}, Paul H. Lee³¹¹, Mostafa Leili²⁸², Aubrey J. Levine¹, Shanshan Li¹⁹⁹, Lee-Ling Lim^{312,313}, Stefan List^{314,315}, Joshua Longbottom³¹⁶, Jaifred Christian F. Lopez^{45,317}, Stefan Lorkowski^{318,319}, Sameh Magdeldin^{320,321}, Hassan Magdy Abd El Razek³²², Muhammad Magdy Abd El Razek³²², Azeem Majeed¹⁹⁶, Afshin Maleki¹⁴², Reza Malekzadeh^{324,325}, Deborah Carvalho Malta³²⁶, Abdullah A. Mamun³²⁷, Navid Manafi^{328,329}, Ana-Laura Manda³³⁰, Morteza Mansourian³³¹, Francisco Rogerlândia Martins-Melo³³², Anthony Masaka³³³, Benjamin Ballard Massenbun³³⁴, Pallab K. Maulik^{335,336}, Benjamin K. Mayala¹, Mohsen Mazidi³³⁷, Martin McKee³³⁸, Ravi Mehrotra³³⁹, Kala M. Mehta³⁴⁰, Gebrekiros Gebremichael Meles⁸⁸, Walter Mendoza³⁴⁴, Ritesh G. Menezes³⁴², Atte Meretoja^{343,344}, Tuomo J. Meretoja^{345,346}, Tomislav Mestrovic^{347,348}, Ted R. Miller^{217,349}, Molly K. Miller-Petrie¹, Edward J. Mills³⁵⁰, George J. Milne³⁵¹, G. K. Mini³⁵², Seyed Mostafa Mir^{353,354}, Hamed Mirjalali³⁵⁵, Erkin M. Mirrakhimov^{356,357}, Efat Mohammadi³⁵⁸, Dara K. Mohammad^{359,360}, Aso Mohammad Darwesh³⁶¹, Naser Mohammad Gholi Merzari³⁶², Ammas Siraj Mohammed³⁶³, Shafiq Mohammed^{364,365}, Ali H. Mokdad^{1,141}, Meziyan Molokhia³⁶⁶, Lorenzo Monasta³⁶⁷, Yoshan Moodley³⁰³, Mahmood Moosazadeh³⁶⁸, Ghobad Moradi^{369,370}, Masoud Moradi^{371,372}, Yousef Moradi³⁷¹, Maziar Moradi-Lakeh⁶⁰, Mehdi Moradinazar⁵⁹, Paula Moraga³⁷², Lidia Morawska³⁷³, Abbas Mospour^{353,374}, Seyyed Meysam Mousavi³⁷⁵, Ulrich Otto Mueller^{376,377}, Atalay Goshu Muluneh³⁷⁸, Ghulam Mustafa^{379,380}, Behnam Nabavizadeh³⁸¹, Mehdi Naderi³⁸², Ahmarshah Jayaraman Nagarajan^{383,384}, Azin Nahvijou³⁸⁵, Farid Najafi³⁸⁶, Vinay Nangia³⁸⁷, Duduzile Edith Ndwandwe³⁸⁸, Nahid Neamati³⁵³, Ionut Negru^{389,390}, Ruxandra Irina Neogi^{391,392}, Josephine W. Ngunjiri³⁹³, Huong Lan Thi Nguyen³⁹⁴, Long Hoang Nguyen³⁹⁵, Son Hoang Nguyen³⁹⁵, Katie R. Nielsen^{396,397}, Dina Nur Anggraini Ningrum^{610,611}, Yirga Legesse Nirayo³⁹⁸, Molly R. Nixon¹, Chukwuodi A. Nnaji^{388,399}, Marzieh Nojomi^{60,400}, Mehdi Noroozi⁴⁰¹, Shirin Nosratnejad⁴⁰², Jean Jacques Noubiap⁴¹, Orayma Nouraei Motlagh²³⁴, Mehdi Orofi-Aseño^{404,405}, Felix Akpojone Ogbo⁴⁰⁶, Kelechi E. Oladimeji^{303,407}, Andrew T. Olagunju^{408,409}, Meysam Olfatfar⁴¹⁰, Solomon Olum^{411,412}, Bolajoko Olubukunola Oluasanya⁴¹³, Mojisola Morenike Oluwasanu⁴¹⁴, Obinna E. Onwujekwe⁴¹⁵, Eyal Oren^{416,417}, Doris D. V. Ortega-Altamirano⁴¹⁸, Alberto Ortiz^{419,420}, Osayomwabo Osarenotor⁴²¹, Frank B. Osei^{422,423}, Aaron E. Osgood-Zimmerman¹, Stanislav S. Otsstavnov^{424,425}, Mayowa Ojo Owolabi⁴²⁶, Mahesh P. A.⁴²⁷, Abdol Sattar Pagheh¹²², Smita Pakhale⁴²⁸, Songhomitra Panda-Jonas⁴²⁹, Animika Pandey¹²¹, Eun-Ke Park⁴³⁰, Hadi Parsian⁵³, Tahereh Pashaei⁴³¹, Sangram Kishor Patel^{431,432}, Veincent Christian Filipino Pepito⁴³³, Alexandre Pereira^{434,435}, Samantha Perkins¹, Brandon V. Pickering¹, Thomas Pilgrim⁴³⁶, Majid Pirestani⁴³⁷, Bakhtiar Piroozii³⁷⁰, Meghdad Pirsahab³, Oleguer Plana-Ripoll⁴³⁸, Hadi Pourjafar^{439,440}, Parul Puri³⁰², Mostafa Qorbani⁴⁴¹, Hedley Quintana¹⁰⁰, Mohammad Rabiee⁴⁴², Navid Rabiee⁷², Amir Radfar^{443,444}, Alireza Rafiei^{445,446}, Fakher Rahim^{447,448}, Zohreh Rahimi⁴⁴⁹, Vafa Rahimi-Movaghar⁴⁵⁰, Shadi Rahimzadeh⁶³, Fatemeh Rajati⁴⁵¹, Sree Bhushan Raju⁴⁵², Azra Ramezankhani^{453,454}, Chhahi Lal Ranabhad^{455,456}, Davide Rasella^{457,458}, Vahid Rasheidi⁴⁵⁹, Lal Rawal^{56,460}, Robert C. Reiner Jr.^{1,141}, Andre M. N. Renzaho⁴⁶¹, Satar Rezaei⁴⁶², Aziz Rezapour³³, Seyed Mohammad Riahi^{463,464}, Ana Isabel Ribeiro⁴⁶⁵, Leonardo Roeber⁴⁶⁶, Elias Merdassa Roro^{467,468}, Max Rose⁴⁶⁹, Gholamreza Roshandel^{324,470}, Daem Roshani⁴⁷¹, Ali Rostami⁴⁷², Enrico Rubagotti^{473,474}, Salvatore Rubino⁴⁷⁵, Siamak Sabour⁴⁶³, Nafis Sadat¹, Ehsan Sadeghi⁵⁹, Reza Saeeedi⁴⁷⁶, Yahya Safari³, Roya Safari-Faramani⁴⁷⁷, Mahdi Safdarian^{450,478}, Amirhossein Sahebkar^{479,480}, Mohammad Zaha Salahshoor⁴⁸¹, Nasir Salam⁴⁸², Payman Salamat^{450,483}, Farkhonde Salehi⁴⁸⁴, Saleh Salehi Zahabi^{485,486}, Yahya Salimi³⁸⁶, Hamideh Salimzadeh³²⁴, Joshua A. Salomon⁴⁸⁷, Evanson Zondani Sambala³⁸⁸, Abdallah M. Samy⁴⁸⁸, Milena M. Santric Milicevic⁴⁸⁹, Bruno Piassi Sao Jose⁴⁹⁰, Sivan Yegnanarayana Iyer Saraswathy^{491,492}, Rodrigo Sarmiento-Suárez⁴⁹³, Benn Sartorius^{141,494}, Brijesh Sathian^{495,496}, Sonia Saxena⁴⁹⁷, Alyssa N. Sbarra¹, Lauren E. Schaeffer¹, David C. Schwebel⁴⁹⁸, Sadaf G. Sepanlou^{324,325}, Seyedmojtaba Seyedmousavi^{499,500}, Faramarz Shaahmadi⁵⁰¹, Masood Ali Shaikh⁵⁰², Mehran Shams-Beyranvand^{63,503}, Amir Shams Shirian⁵⁰⁴, Morteza Shamsizadeh⁵⁰⁵, Kiomars Sharafi³, Mehdi Shari^{506,507}, Mahdi Sharif-Alhosseini⁴⁵⁰, Hamid Sharif⁵⁰⁸, Jayendra Sharma⁵⁰⁹, Rajesh Sharma⁵¹⁰, Aziz Sheikh^{511,512}, Chloe Shields¹, Mika Shigematsu⁵¹³, Rahman Shiri⁵¹⁴, Ivy Shiue⁵¹⁵, Kerem Shuval¹⁹⁸, Tariq J. Siddiqi²⁷⁵, João Pedro Silva¹¹⁸, Jasvinder A. Singh^{516,517}, Dhirendra Narain Sinha^{518,519}, Malede Mequanent Sisay^{378,520}, Solomon Sisay⁵²¹, Karen Sliwa⁴⁰³, David L. Smith^{1,141}, Ranjani Somayaji^{522,523}, Moslem Soofi⁵²⁴, Joan B. Soriano^{525,526}, Chandrashekar T. Sreeramreddy⁵²⁷, Agus Sudaryanto⁵²⁸, Mu'awiyah Babale Sufiyan⁵²⁹, Bryan L. Sykes⁵³⁰, P. N. Sylaja⁵³¹, Rafael Tabares-Seisdedos^{532,533}, Karen M. Tabb⁵³⁴, Takahiro Tabuchi⁵³⁵, Nuno Taveira^{536,537}, Mohamad-Hani Temsal^{538,539}, Abdullah Suleiman Terkawi^{540,541}, Zemu Tadesse Tessema³⁷⁸, Kavumpurathu Raman Thankappan⁵⁴², Sathish Thirunavukkarasu⁵⁴³, Quyen G. To⁵⁴⁴, Marcos Roberto Tovani-Palone⁵⁴⁵, Bach Xuan Tran⁵⁴⁶, Khanh Bao Tran^{547,548}, Irfan Ullah^{549,550}, Muhammad Shariq Usman²⁷⁵, Olealek A. Uthman⁵⁵¹, Amir Vahedian-Azimi^{552,553}, Pascual R. Valdez^{554,555}, Job F. M. van Boven^{556,557}, Tommi Juhani Vasankari⁵⁵⁸, Yasser Vasseghian⁴⁶², Yousef Veisani⁵⁵⁹, Narayanaswamy Venkatasubramanian^{560,561}, Francesco S. Violante^{562,563}, Sergey Konstantinovich Vladimirov^{564,565}, Vasily Vlassov⁵⁶⁶, Theo Vos^{1,141}, Giang Thu Vu²²⁰, Isidora S. Vujcic⁷⁷, Yasir Waheed⁵⁶⁷, Jon Wakefield⁵⁶⁸, Haidong Wang^{1,141}, Yangfang Wang⁵⁶⁹, Yuan-Pang Wang⁵⁷⁰, Joseph L. Ward⁵⁷¹, Robert C. Weintraub^{572,573}, Kidu Gidey Weldegionnes³⁹⁸, Girmay Teklay Weldesamuel⁵⁷⁴, Ronny Westerman⁵⁷⁵, Charles Shuey Widsongwe^{576,577}, Dawit Zewdu Wondafrahs^{578,579}, Lauren Woyczynski¹, Ai-Min Wu⁵⁸⁰, Gelin Xu⁵⁸¹, Abbas Yadegar⁵⁸⁵, Tomohide Yamada⁵⁸², Vahid Yazdi-Feizyabadi^{583,584}, Christoph Sabo Yilgwan^{585,586}, Paul Yip^{587,588}, Naohiro Yonemoto⁵⁸⁹, Javad Yousefi Lebni³³¹, Mustafa Z. Younis^{590,591}, Mahmoud Yousefiard⁵⁹², Hebat-Allah Salah A. Yousof⁵⁹³, Chuanhua Yu^{569,594}, Hasan Yusefzadeh⁵⁹⁵, Erfan Zabeh^{596,597}, Telma Zahrihan Moghadam^{33,598}, Sojib Bin Zaman^{599,600}, Mohammad Zamani⁶⁰¹, Hamed Zandian^{598,602}, Alireza Zangeneh⁶⁰³, Taddese Alemu Zerfu^{604,605}, Yunqun Zhang^{606,607}, Arash Ziapour³³¹, Sanjay Zodpey⁶⁰⁸, Christopher J. L. Murray^{1,141,613} & Simon I. Hay^{1,141,613*}

¹Institute for Health Metrics and Evaluation, University of Washington, Seattle, WA, USA.

²Department of Nutrition, Tabriz University of Medical Sciences, Tabriz, Iran. ³Kermanshah University of Medical Sciences, Kermanshah, Iran. ⁴Department of Neurology, Cairo University, Cairo, Egypt. ⁵Department of Parasitology and Mycology, Jahrom University of Medical Sciences, Jahrom, Iran. ⁶The Institute of Pharmaceutical Sciences, Tehran University of Medical Sciences, Tehran, Iran. ⁷Multiple Sclerosis Research Center, Tehran University of Medical Sciences, Tehran, Iran. ⁸Department of Epidemiology, Arak University of Medical Sciences, Arak, Iran. ⁹Department of Public Health, Ministry of Health, Riyadh, Saudi Arabia. ¹⁰Research Department, Philippine Institute for Development Studies, Quezon City, The Philippines.

¹¹Department of Preventive Medicine, Dongguk University, Gyeongju, South Korea. ¹²Department of Community Medicine, Kathmandu University, Devdaha, Nepal. ¹³College of Medicine, University College Hospital, Ibadan, Nigeria. ¹⁴School of Medicine, Cardiff University, Cardiff, UK. ¹⁵School of Health, Ardabil University of Medical Science, Ardabil, Iran. ¹⁶Department of Community Medicine, Zabol University of Medical Sciences, Zabol, Iran. ¹⁷Department of Epidemiology and Biostatistics, Qom University of Medical Sciences, Qom, Iran. ¹⁸School of Pharmacy, University of Lincoln, Lincoln, UK. ¹⁹Environmental Technologies Research Center, Ahvaz Jundishapur University of Medical Sciences, Ahvaz, Iran. ²⁰Department of Parasitology and Mycology, Tabriz University of Medical Sciences, Tabriz, Iran. ²¹James P. Grant School of Public Health, Brac University, Dhaka, Bangladesh. ²²Health Systems and Population Studies Division, International Centre for Diarrhoeal Disease Research Bangladesh, Dhaka, Bangladesh. ²³Department of Medical Laboratory Science, Bahir Dar University, Bahir

Dar, Ethiopia. ²⁴Epidemiology and Medical Statistics, University of Ibadan, Ibadan, Nigeria. ²⁵Evidence Based Practice Center, Mayo Clinic Foundation for Medical Education and Research, Rochester, MN, USA. ²⁶Prevention Division, Queensland Health, Herston, Queensland, Australia. ²⁷School of Health Sciences, Madda Walabu University, Bale Goba, Ethiopia. ²⁸Institute of Public Health, University of Gondar, Gondar, Ethiopia. ²⁹Research School of Population Health, Australian National University, Canberra, Australian Capital Territory, Australia. ³⁰Qazvin University of Medical Sciences, Qazvin, Iran. ³¹Department of Health Care Management and Economics, Urmia University of Medical Science, Urmia, Iran. ³²Health Economics Department, Iran University of Medical Sciences, Tehran, Iran. ³³Health Management and Economics Research Center, Iran University of Medical Sciences, Tehran, Iran. ³⁴Department of Health Policy and Management, Kuwait University, Safat, Kuwait. ³⁵International Centre for Casemix and Clinical Coding, National University of Malaysia, Bandar Tun Razak, Malaysia. ³⁶Faculty of Public Health and Tropical Medicine, Jazan University, Jazan, Saudi Arabia. ³⁷Jazan University, Jazan, Saudi Arabia. ³⁸Medical Research Center, Jazan University, Jazan, Saudi Arabia. ³⁹Department of Medical Parasitology, Sana'a University, Sana'a, Yemen. ⁴⁰King Saud University, Riyadh, Saudi Arabia. ⁴¹Research Group in Health Economics, Universidad de Cartagena, Cartagena, Colombia. ⁴²Research Group in Hospital Management and Health Policies, Universidad de la Costa, Barranquilla, Colombia. ⁴³Biomedical Science, University of Cape Coast, Cape Coast, Ghana. ⁴⁴Health Services Management Department, Arak University of Medical Sciences, Arak, Iran. ⁴⁵Department of Epidemiology and Biostatistics, University of the Philippines Manila, Manila, The Philippines. ⁴⁶Online Programs for Applied Learning, Johns Hopkins University, Baltimore, MD, USA. ⁴⁷Department of Medicine, University of Thessaly, Volos, Greece. ⁴⁸Social Determinants of Health Research Center, Rafsanjan University of Medical Sciences, Rafsanjan, Iran. ⁴⁹Research Center for Evidence Based Medicine-Health Management and Safety Promotion Research Institute, Tabriz University of Medical Sciences, Tabriz, Iran. ⁵⁰Department of Health Policy and Administration, University of the Philippines Manila, Manila, The Philippines. ⁵¹Department of Applied Social Sciences, Hong Kong Polytechnic University, Hong Kong, China. ⁵²Department of Health Promotion and Education, Tehran University of Medical Sciences, Tehran, Iran. ⁵³School of Health Sciences, Birmingham City University, Birmingham, UK. ⁵⁴School of Nursing and Midwifery, Saveh University of Medical Sciences, Saveh, Iran. ⁵⁵Social Determinants of Health Research Center, Saveh University of Medical Sciences, Saveh, Iran. ⁵⁶School of Science and Health, Western Sydney University, Penrith, New South Wales, Australia. ⁵⁷Oral Health Services, Sydney Local Health District, Sydney, New South Wales, Australia. ⁵⁸Department of Community Health Sciences, University of Manitoba, Winnipeg, Manitoba, Canada. ⁵⁹Research Center for Environmental Determinants of Health, Kermanshah University of Medical Sciences, Kermanshah, Iran. ⁶⁰Preventive Medicine and Public Health Research Center, Iran University of Medical Sciences, Tehran, Iran. ⁶¹Faculty of Medicine, Tehran University of Medical Sciences, Tehran, Iran. ⁶²Education Development Center, Mashhad University of Medical Sciences, Mashhad, Iran. ⁶³Non-communicable Diseases Research Center, Tehran University of Medical Sciences, Tehran, Iran. ⁶⁴Center for Clinical Global Health Education, Johns Hopkins University, Baltimore, MD, USA. ⁶⁵Dr D. Y. Patil Medical College, Pune, India. ⁶⁶The Judith Lumley Centre, La Trobe University, Melbourne, Victoria, Australia. ⁶⁷General Office for Research and Technological Transfer, Peruvian National Institute of Health, Lima, Peru. ⁶⁸Department of Family and Community Health, University of Health and Allied Sciences, Ho, Ghana. ⁶⁹Center for Infectious Diseases Research, Babol, Iran. ⁷⁰Public Health Risk Sciences Division, Public Health Agency of Canada, Toronto, Ontario, Canada. ⁷¹Department of Nutritional Sciences, University of Toronto, Toronto, Ontario, Canada. ⁷²Department of Chemistry, Sharif University of Technology, Tehran, Iran. ⁷³Tissue Engineering and Applied Cell Sciences Division, Tarbiat Modares University, Tehran, Iran. ⁷⁴Division of Diseases, Advanced Technologies Research Group, Tehran, Iran. ⁷⁵School of Nursing and Midwifery, Iran University of Medical Sciences, Tehran, Iran. ⁷⁶Clinic for Infectious and Tropical Diseases, Clinical Center of Serbia, Belgrade, Serbia. ⁷⁷Faculty of Medicine, University of Belgrade, Belgrade, Serbia. ⁷⁸Barcelona Institute for Global Health, University of Barcelona, Barcelona, Spain. ⁷⁹Catalan Institution for Research and Advanced Studies (ICREA), Barcelona, Spain. ⁸⁰Department of Psychiatry, Melbourne Medical School, Melbourne, Victoria, Australia. ⁸¹Health Human Resources Research Center, Shiraz University of Medical Sciences, Shiraz, Iran. ⁸²Department of Community Medicine, Gandhi Medical College Bhopal, Bhopal, India. ⁸³Department of Neuroscience, Mario Negri Institute for Pharmacological Research, Milan, Italy. ⁸⁴Social Determinants of Health Research Center, Lorestan University of Medical Sciences, Khorramabad, Iran. ⁸⁵Hepatitis Research Center, Lorestan University of Medical Sciences, Khorramabad, Iran. ⁸⁶Pharmacoeconomics and Social Pharmacy, Mekelle University, Mekelle, Ethiopia. ⁸⁷School of Forestry and Environmental Studies, Yale University, New Haven, CT, USA. ⁸⁸Department of Public Health, Arba Minch University, Arba Minch, Ethiopia. ⁸⁹Hubert Department of Global Health, Emory University, Atlanta, GA, USA. ⁹⁰Department of Global Health, University of South Florida, Tampa, FL, USA. ⁹¹London School of Hygiene & Tropical Medicine, London, UK. ⁹²Nepal Academy of Science & Technology, Patan, Nepal. ⁹³The Centre for Global Child Health, Hospital for Sick Children, University of Toronto, Toronto, Ontario, Canada. ⁹⁴Center of Excellence in Women and Child Health, Aga Khan University, Karachi, Pakistan. ⁹⁵Social Determinants of Health Research Center, Babol University of Medical Sciences, Babol, Iran. ⁹⁶Department of Veterinary Medicine, Karaj Islamic Azad University, Kermanshah, Iran. ⁹⁷Department of Psychology, Ohio State University, Columbus, OH, USA. ⁹⁸Psychiatry and Behavioral Health Department, Ohio State University, Columbus, OH, USA. ⁹⁹Neuroscience Department, Institute for Scientific Research and High Technology Services, City of Knowledge, Panama. ¹⁰⁰Gorgas Memorial Institute for Health Studies, Panama, Panama. ¹⁰¹Big Data Institute, Li Ka Shing Centre for Health Information and Discovery, University of Oxford, Oxford, UK. ¹⁰²Department of Community Medicine, Employees' State Insurance Model Hospital, Bangalore, India. ¹⁰³Department for Health Care Management, Technical University of Berlin, Berlin, Germany. ¹⁰⁴School of Population and Public Health, University of British Columbia, Vancouver, British Columbia, Canada. ¹⁰⁵Al Shifa School of Public Health, Al Shifa Trust Eye Hospital, Rawalpindi, Pakistan. ¹⁰⁶Centre for Population Health Sciences, Nanyang Technological University, Singapore, Singapore. ¹⁰⁷Global Ehealth Unit, Imperial College London, London, UK. ¹⁰⁸Department of Population and Health, Metropolitan Autonomous University, Mexico City, Mexico. ¹⁰⁹Colombian National Health Observatory, National Institute of Health, Bogota, Colombia. ¹¹⁰Epidemiology and Public Health Evaluation Group, National University of Colombia, Bogota, Colombia. ¹¹¹Mary MacKillop Institute for Health Research, Australian Catholic University, Melbourne, Victoria, Australia. ¹¹²School of Public Health, University of Hong Kong, Hong Kong, China. ¹¹³Department of Obstetrics and Gynaecology, University of Gondar, Gondar, Ethiopia. ¹¹⁴Division of Epidemiology, National Institute of Cholera and Enteric Diseases, Kolkata, India. ¹¹⁵Faculty of Biology, Hanoi National University of Education, Hanoi, Vietnam. ¹¹⁶Department of Rheumatology, University of Oxford, Oxford, UK. ¹¹⁷Medical Research Council Lifecourse Epidemiology Unit, University of Southampton, Southampton, UK. ¹¹⁸Applied Molecular Biosciences Unit (UCIBIO), University of Porto, Porto, Portugal. ¹¹⁹Institute of Public Health Kalyani, Kalyani, India. ¹²⁰School of Health Science, Orebro University, Orebro, Sweden. ¹²¹Public Health Foundation of India, Gurugram, India. ¹²²Toxoplasmosis Research Center, Mazandaran University of Medical Sciences, Sari, Iran. ¹²³Department of General Surgery, Carol Davila University of Medicine and Pharmacy, Bucharest, Romania. ¹²⁴Department of Surgery, Clinical Emergency Hospital St Pantelimon, Bucharest, Romania. ¹²⁵Heidelberg Institute of Global Health (HIGH), Heidelberg University, Heidelberg, Germany. ¹²⁶Bahir Dar University, Bahir Dar, Ethiopia. ¹²⁷School of Pharmacy, Aksum University, Aksum, Ethiopia. ¹²⁸Addis Ababa University, Addis Ababa, Ethiopia. ¹²⁹School of Public Health, Addis Ababa University, Addis Ababa, Ethiopia. ¹³⁰Department of Global Health and Infection, Brighton and Sussex Medical School, Brighton, UK. ¹³¹Division of Cardiology, Atlanta Veterans Affairs Medical Center, Decatur, GA, USA. ¹³²Public Health Nutrition, Bahir Dar University, Bahir Dar, Ethiopia. ¹³³Centre for Atmospheric Sciences, Indian Institute of Technology Delhi, New Delhi, India. ¹³⁴Department of Community Medicine, University of Peradeniya, Peradeniya, Sri Lanka. ¹³⁵Health Research Section, Nepal Health Research Council, Kathmandu, Nepal. ¹³⁶Center of Complexity Sciences, National Autonomous University of Mexico, Mexico City, Mexico. ¹³⁷Facultad de Medicina Veterinaria y Zootecnia, Autonomous University of Sinaloa, Culiacan Rosales, Mexico. ¹³⁸Department of Health Policy and Economy, Tabriz University of Medical Sciences, Tabriz, Iran. ¹³⁹School of Medicine, Federal University of Bahia, Salvador, Brazil. ¹⁴⁰Diretoria Médica, Roberto Santos General Hospital, Salvador, Brazil. ¹⁴¹Department of Health Metrics Sciences, School of Medicine, University of Washington, Seattle, WA, USA. ¹⁴²Environmental Health Research Center, Kurdistan University of Medical Sciences, Sanandaj, Iran. ¹⁴³Clinical Epidemiology and Biostatistics, University of Newcastle, Newcastle, New South Wales, Australia. ¹⁴⁴Department of Toxicology and Pharmacology, Tabriz University of Medical Sciences, Tabriz, Iran. ¹⁴⁵Department of Basic Sciences, Maragheh University of Medical Sciences, Maragheh, Iran. ¹⁴⁶National Institute for Health Researchers, Tehran University of Medical Sciences, Tehran, Iran. ¹⁴⁷Medical Research Institute, Alexandria University, Alexandria, Egypt. ¹⁴⁸Department of Clinical Pathology, Mansoura University, Mansoura, Egypt. ¹⁴⁹Pediatric Dentistry and Dental Public Health, Alexandria University, Alexandria, Egypt. ¹⁵⁰Preventive Dental Sciences, Imam Abdulrahman Bin Faisal University, Dammam, Saudi Arabia. ¹⁵¹Department of Public Health Sciences, Karolinska Institutet, Stockholm, Sweden. ¹⁵²Ophthalmic Epidemiology Research Center, Shahrood University of Medical Sciences, Shahrood, Iran. ¹⁵³Department of Microbiology and Immunology, Suez Canal University, Ismailia, Egypt. ¹⁵⁴Epidemiology and Population Health, British Columbia Centre for Excellence in HIV/AIDS, Vancouver, British Columbia, Canada. ¹⁵⁵Faculty of Health Sciences, Simon Fraser University, Burnaby, British Columbia, Canada. ¹⁵⁶Babol University of Medical Sciences, Babol, Iran. ¹⁵⁷College of Medicine, Imam Muhammad Ibn Saud Islamic University, Riyadh, Saudi Arabia. ¹⁵⁸Department of Parasitology, Mazandaran University of Medical Sciences, Sari, Iran. ¹⁵⁹Department of Psychology, Federal University of Sergipe, Sao Cristovao, Brazil. ¹⁶⁰Social Determinants of Health Research Center, Hamadan University of Medical Sciences, Hamadan, Iran. ¹⁶¹Environmental Health Engineering, Tehran University of Medical Sciences, Tehran, Iran. ¹⁶²Department of Environmental Health Engineering, Ardabil University of Medical Science, Ardabil, Iran. ¹⁶³Department of Public Health Nutrition, Bahir Dar University, Bahir Dar, Ethiopia. ¹⁶⁴Department of Neurobiology, Karolinska Institutet, Stockholm, Sweden. ¹⁶⁵Division of Neurology, University of Ottawa, Ottawa, Ontario, Canada. ¹⁶⁶Center for Biotechnology and Fine Chemistry, Catholic University of Portugal, Porto, Portugal. ¹⁶⁷Psychiatry Department, Kaiser Permanente, Fontana, CA, USA. ¹⁶⁸Department of Health Sciences, A.T. Still University, Mesa, AZ, USA. ¹⁶⁹Department of Public Health Medicine, Bielefeld University, Bielefeld, Germany. ¹⁷⁰Institute of Gerontology, National Academy of Medical Sciences of Ukraine, Kyiv, Ukraine. ¹⁷¹Abadan School of Medical Sciences, Abadan, Iran. ¹⁷²Clinical Medicine and Wits Reproductive Health and HIV Institute, University of the Witwatersrand, Johannesburg, South Africa. ¹⁷³Gene Expression & Regulation Program, Cancer Institute (W.I.A.), Philadelphia, PA, USA. ¹⁷⁴Department of Dermatology, Kobe University, Kobe, Japan. ¹⁷⁵Department of Environmental Health Science, Mario Negri Institute for Pharmacological Research, Milan, Italy. ¹⁷⁶Mekelle University, Mekelle, Ethiopia. ¹⁷⁷Dr Tewelde Legesse Health Sciences College, Mekelle, Ethiopia. ¹⁷⁸Department of Epidemiology, Jimma University, Jimma, Ethiopia. ¹⁷⁹School of Nursing, Mekelle University, Mekelle, Ethiopia. ¹⁸⁰Nursing Department, Aksum University, Aksum, Ethiopia. ¹⁸¹Vaccines Department, Pfizer, Collegeville, PA, USA. ¹⁸²Agency of Preventive Medicine, Paris, France. ¹⁸³Department of Pharmacy, Wollo University, Dessie, Ethiopia. ¹⁸⁴Health Research Institute, Babol University of Medical Sciences, Babol, Iran. ¹⁸⁵Department of Neurology, Tehran University of Medical Sciences, Tehran, Iran. ¹⁸⁶Department of Health Services Management, Iran University of Medical Sciences, Tehran, Iran. ¹⁸⁷Unit of Academic Primary Care, University of Warwick, Coventry, UK. ¹⁸⁸Adelaide Medical School, University of Adelaide, Adelaide, South Australia, Australia. ¹⁸⁹Department of Chemistry, University of Porto, Porto, Portugal. ¹⁹⁰REQUIMTE/LAQV, Porto, Portugal. ¹⁹¹Nursing and Health Sciences Department, University of Massachusetts Boston, Boston, MA, USA. ¹⁹²Department of Biostatistics and Epidemiology, University of Oklahoma, Oklahoma City, OK, USA. ¹⁹³Department of Health and Social Affairs, Government of the Federated States of Micronesia, Palikir, Federated States of Micronesia. ¹⁹⁴Occupational and Environmental Epidemiology Section, Cancer Prevention and Research Institute, Florence, Italy. ¹⁹⁵Postgraduate Program in Epidemiology, Federal University of Rio Grande do Sul, Porto Alegre, Brazil. ¹⁹⁶Department of Primary Care and Public Health, Imperial College London, London, UK. ¹⁹⁷Health Improvement Directorate, Public Health England, London, UK. ¹⁹⁸School of Public Health, University of Haifa, Haifa, Israel. ¹⁹⁹School of Public Health and Preventive Medicine, Monash University, Melbourne, Victoria, Australia. ²⁰⁰Department of Epidemiology

- and Biostatistics, Zhengzhou University, Zhengzhou, China.²⁰¹Department of Pharmacology, Tehran University of Medical Sciences, Tehran, Iran.²⁰²Obesity Research Center, Research Institute for Endocrine Sciences, Shahid Beheshti University of Medical Sciences, Tehran, Iran.²⁰³Department of Radiology, Johns Hopkins University, Baltimore, MD, USA.²⁰⁴Global and Community Mental Health Research Group, University of Macau, Macao, China.²⁰⁵School of Health and Environmental Studies, Hamdan Bin Mohammed Smart University, Dubai, United Arab Emirates.²⁰⁶Tabriz University of Medical Sciences, Tabriz, Iran.²⁰⁷Biomedical Research Networking Center for Mental Health Network (CIBERSAM), Madrid, Spain.²⁰⁸Research and Development Unit, San Juan de Dios Sanitary Park, Sant Boi De Llobregat, Spain.²⁰⁹School of Nutrition and Food Sciences, Tabriz University of Medical Sciences, Tabriz, Iran.²¹⁰Healthcare Management, Maragheh University of Medical Sciences, Maragheh, Iran.²¹¹Department of Microbiology, Tehran University of Medical Sciences, Tehran, Iran.²¹²Department of Microbiology, Maragheh University of Medical Sciences, Maragheh, Iran.²¹³School of Nursing and Midwifery Tabriz University of Medical Sciences, Tabriz, Iran.²¹⁴Independent Consultant, Tabriz, Iran.²¹⁵Public Health Department, Mizan-Tepi University, Teppi, Ethiopia.²¹⁶Unit of Epidemiology and Social Medicine, University Hospital Antwerp, Antwerp, Belgium.²¹⁷School of Public Health, Curtin University, Bentley, Western Australia, Australia.²¹⁸Medical Biology Research Center, Kermanshah University of Medical Sciences, Kermanshah, Iran.²¹⁹Population Health, Baker Heart and Diabetes Institute, Melbourne, Victoria, Australia.²²⁰Center of Excellence in Behavioral Medicine, Nguyen Tat Thanh University, Ho Chi Minh, Vietnam.²²¹Social Determinants of Health Research Center, Guilan Road Trauma Research Center, Guilan University of Medical Sciences, Rasht, Iran.²²²Guilan Road Trauma Research Center, Guilan University of Medical Sciences, Rasht, Iran.²²³Radiology and Nuclear Medicine Department, Kermanshah University of Medical Sciences, Kermanshah, Iran.²²⁴Department of Pharmacology and Therapeutics, University of Dhaka, Dhaka, Bangladesh.²²⁵Department of Epidemiology and Biostatistics, Tehran University of Medical Sciences, Tehran, Iran.²²⁶Computer Science Department, University of Human Development, Sulaimaniyah, Iraq.²²⁷Department of Internal Medicine, Bucharest Emergency Hospital, Bucharest, Romania.²²⁸Faculty of Dentistry, Carol Davila University of Medicine and Pharmacy, Bucharest, Romania.²²⁹Clinical Legal Medicine, National Institute of Legal Medicine Mina Minovici, Bucharest, Romania.²³⁰Division of Information and Computing Technology, Hamad Bin Khalifa University, Doha, Qatar.²³¹Qatar Foundation for Education, Science and Community Development, Doha, Qatar.²³²Faculty of Medicine Tunis, Medicine School of Tunis, Baab Saadoun, Tunisia.²³³Department of Community Medicine, University of Ibadan, Ibadan, Nigeria.²³⁴Department of Public Health, Lorestan University of Medical Sciences, Khorramabad, Iran.²³⁵Global Health and Development Department, Taipei Medical University, Taipei City, Taiwan.²³⁶Research Institute for Endocrine Sciences, Shahid Beheshti University of Medical Sciences, Tehran, Iran.²³⁷MRC Epidemiology Unit, University of Cambridge, Cambridge, UK.²³⁸Harvard University, Boston, MA, USA.²³⁹Institute for Physical Activity and Nutrition, Deakin University, Burwood, Victoria, Australia.²⁴⁰Sydney Medical School, University of Sydney, Sydney, New South Wales, Australia.²⁴¹Institute of Family Medicine and Public Health, University of Tartu, Tartu, Estonia.²⁴²Psychosis Department, Babol Nushirvani University of Technology, Babol, Iran.²⁴³Psychiatric Department, Kermanshah University of Medical Sciences, Kermanshah, Iran.²⁴⁴Department of Medical Mycology, Mazandaran University of Medical Sciences, Sari, Iran.²⁴⁵Faculty of Graduate Studies, University of Colombo, Colombo, Sri Lanka.²⁴⁶Institute of Medicine, University of Colombo, Colombo, Sri Lanka.²⁴⁷School of Midwifery, A.T. Still University, Mesa, AZ, USA.²⁴⁸Environmental Research Center, Duke Kunshan University, Kunshan, China.²⁴⁹Department of Medicine, University of Miami, Atlantis, FL, USA.²⁵⁰Department of Ophthalmology, Heidelberg University, Heidelberg, Germany.²⁵¹Beijing Institute of Ophthalmology, Beijing Tongren Hospital, Beijing, China.²⁵²Social Determinants of Health Research Center, University of Social Welfare and Rehabilitation Sciences, Tehran, Iran.²⁵³Faculty of Medicine and Health Sciences, University of Opole, Opole, Poland.²⁵⁴Department of Family Medicine and Public Health, University of Opole, Opole, Poland.²⁵⁵Minimally Invasive Surgery Research Center, Iran University of Medical Sciences, Tehran, Iran.²⁵⁶Department of Nutrition and Dietetics, Mekelle University, Mekelle, Ethiopia.²⁵⁷Mazandaran University of Medical Sciences, Sari, Iran.²⁵⁸Sfahani University of Medical Sciences, Isfahan, Iran.²⁵⁹Social Determinants of Health Research Center, Qazvin University of Medical Sciences, Qazvin, Iran.²⁶⁰Department of Epidemiology, Hamadan University of Medical Sciences, Hamadan, Iran.²⁶¹Research and Development, Australian Red Cross Blood Service, Sydney, New South Wales, Australia.²⁶²School of Public Health and Community Medicine, University of New South Wales, Sydney, New South Wales, Australia.²⁶³Hematologic Malignancies Research Center, Tehran University of Medical Sciences, Tehran, Iran.²⁶⁴Hematology-Oncology and Stem Cell Transplantation Research Center, Tehran University of Medical Sciences, Tehran, Iran.²⁶⁵Department of Anesthesiology & Pain Medicine, University of Washington, Seattle, WA, USA.²⁶⁶Odel Campus, University of Nairobi, Nairobi, Kenya.²⁶⁷Michigan State University, East Lansing, MI, USA.²⁶⁸Tabriz Health Management Research Center, Tabriz University of Medical Sciences, Tabriz, Iran.²⁶⁹National Institute for Health Research (NIHR), Tehran University of Medical Sciences, Tehran, Iran.²⁷⁰Department of Public Health and Community Medicine, Jordan University of Science and Technology, Ramtha, Jordan.²⁷¹Social Determinants of Health Research Center, Ahvaz Jundishapur University of Medical Sciences, Ahvaz, Iran.²⁷²Epidemiology and Biostatistics Department, Health Services Academy, Islamabad, Pakistan.²⁷³Population Studies, International Institute for Population Sciences, Mumbai, India.²⁷⁴Department of Internal Medicine, John H. Stroger Jr Hospital of Cook County, Chicago, IL, USA.²⁷⁵Department of Internal Medicine, Dow University of Health Sciences, Karachi, Pakistan.²⁷⁶Institute of Health Policy and Management, Seoul National University, Seoul, South Korea.²⁷⁷Department of Health Policy and Management, Seoul National University, Seoul, South Korea.²⁷⁸Faculty of Health and Wellbeing, Sheffield Hallam University, Sheffield, UK.²⁷⁹Department of Arts and Sciences, Ohio University, Zanesville, OH, USA.²⁸⁰Internal Medicine and Gastroenterology Department, National Hepatology and Tropical Research Institute, Cairo, Egypt.²⁸¹Department of Medical Parasitology, Cairo University, Cairo, Egypt.²⁸²Department of Environmental Health Engineering, Hamadan University of Medical Sciences, Hamadan, Iran.²⁸³Department of Public Health, Mazandaran University of Medical Sciences, Sari, Iran.²⁸⁴Department of Nutrition and Health Science, Ball State University, Muncie, IN, USA.²⁸⁵School of Public Health, Kermanshah University of Medical Sciences, Kermanshah, Iran.²⁸⁶School of Medicine, Xiamen University Malaysia, Sepang, Malaysia.²⁸⁷Department of Nutrition, Simmons College, Boston, MA, USA.²⁸⁸Department of Health Management and Health Economics, Kristiania University College, Oslo, Norway.²⁸⁹Department of Health Services Policy and Management, University of South Carolina, Columbia, SC, USA.²⁹⁰Nursing and Health Promotion, Oslo Metropolitan University, Oslo, Norway.²⁹¹Department of Public Health, Debre Berhan University, Debre Berhan, Ethiopia.²⁹²Independent Consultant, Jakarta, Indonesia.²⁹³Department of Internal and Pulmonary Medicine, Sheri Kashmir Institute of Medical Sciences, Srinagar, India.²⁹⁴CIBERSAM, San Juan de Dios Sanitary Park, Sant Boi De Llobregat, Spain.²⁹⁵Department of Zoology, University of Oxford, Oxford, UK.²⁹⁶Medical School, Harvard University, Boston, MA, USA.²⁹⁷Department of Anthropology, Panjab University, Chandigarh, India.²⁹⁸Family and Community Health, University of Health and Allied Sciences, Ho, Ghana.²⁹⁹Psychology and Health Promotion, University of Kwazulu-Natal, Durban, South Africa.³⁰⁰Department of Psychiatry, University of Nairobi, Nairobi, Kenya.³⁰¹Department of Psychology, University College London, London, UK.³⁰²International Institute for Population Sciences, Mumbai, India.³⁰³Department of Public Health Medicine, University of Kwazulu-Natal, Durban, South Africa.³⁰⁴Nursing, St John of God Hospital, Duayaw Nkwana, Ghana.³⁰⁵Nuffield Department of Population Health, University of Oxford, Oxford, UK.³⁰⁶Oxford Biomedical Research Centre, National Institute for Health Research (NIHR), Oxford, UK.³⁰⁷Department of Pediatrics, Post Graduate Institute of Medical Education and Research, Chandigarh, India.³⁰⁸Department of Community and Family Medicine, Academy of Medical Science, Baghdad, Iraq.³⁰⁹Department of Medical Sciences, Uppsala University, Uppsala, Sweden.³¹⁰Department of Clinical Chemistry and Pharmacology, Uppsala University Hospital, Uppsala, Sweden.³¹¹School of Nursing, Hong Kong Polytechnic University, Hong Kong, China.³¹²Department of Medicine, University of Malaya, Kuala Lumpur, Malaysia.³¹³Department of Medicine and Therapeutics, The Chinese University of Hong Kong, Shatin, China.³¹⁴Department of Dentistry, Radboud University, Nijmegen, The Netherlands.³¹⁵Section for Translational Health Economics, Heidelberg University Hospital, Heidelberg, Germany.³¹⁶Department of Vector Biology, Liverpool School of Tropical Medicine, Liverpool, UK.³¹⁷Alliance for Improving Health Outcomes, Quezon City, The Philippines.³¹⁸Institute of Nutrition, Friedrich Schiller University Jena, Jena, Germany.³¹⁹Competence Cluster for Nutrition and Cardiovascular Health (NUTRICARD), Jena, Germany.³²⁰Physiology Department, Suez Canal University, Ismailia, Egypt.³²¹Proteomics and Metabolomics Unit, Suez Canal University, Ismailia, Egypt.³²²Department of Cardiology, Damietta University, Damietta, Egypt.³²³Ophthalmology Department, Aswan Faculty of Medicine, Aswan, Egypt.³²⁴Digestive Diseases Research Institute, Tehran University of Medical Sciences, Tehran, Iran.³²⁵Non-communicable Diseases Research Center, Shiraz University of Medical Sciences, Shiraz, Iran.³²⁶Department of Maternal and Child Nursing and Public Health, Federal University of Minas Gerais, Belo Horizonte, Brazil.³²⁷Institute for Social Science Research, The University of Queensland, Brisbane, Queensland, Australia.³²⁸Ophthalmology Department, Iran University of Medical Sciences, Tehran, Iran.³²⁹Department of Ophthalmology, University of Manitoba, Winnipeg, Manitoba, Canada.³³⁰Surgery Department, Emergency University Hospital Bucharest, Bucharest, Romania.³³¹Department of Health Education and Health Promotion, Iran University of Medical Sciences, Tehran, Iran.³³²Campus Caucaia, Federal Institute of Education, Science and Technology of Ceará, Caucaia, Brazil.³³³Faculty of Health and Education, Botho University-Botswana, Gaborone, Botswana.³³⁴Division of Plastic Surgery, University of Washington, Seattle, WA, USA.³³⁵School of Medicine, University of New South Wales, Sydney, New South Wales, Australia.³³⁶Research Department, The George Institute for Global Health, New Delhi, India.³³⁷Department of Biology and Biological Engineering, Chalmers University of Technology, Gothenburg, Sweden.³³⁸Department of Health Services Research and Policy, London School of Hygiene & Tropical Medicine, London, UK.³³⁹Preventive Oncology Department, National Institute of Cancer Prevention and Research, Noida, India.³⁴⁰Department of Epidemiology and Biostatistics, University of California San Francisco, San Francisco, CA, USA.³⁴¹Peru Country Office, United Nations Population Fund (UNFPA), Lima, Peru.³⁴²Forensic Medicine Division, Imam Abdulrahman Bin Faisal University, Dammam, Saudi Arabia.³⁴³Neurocenter, Helsinki University Hospital, Helsinki, Finland.³⁴⁴School of Health Sciences, University of Melbourne, Parkville, Victoria, Australia.³⁴⁵Breast Surgery Unit, Helsinki University Hospital, Helsinki, Finland.³⁴⁶University of Helsinki, Helsinki, Finland.³⁴⁷Clinical Microbiology and Parasitology Unit, Dr Zora Profciz Polyclinic, Zagreb, Croatia.³⁴⁸University Centre Varazdin, University North, Varazdin, Croatia.³⁴⁹Pacific Institute for Research & Evaluation, Calverton, MD, USA.³⁵⁰Health, Evidence and Impact, McMaster University, Hamilton, Ontario, Canada.³⁵¹Department of Computer Science and Software Engineering, University of Western Australia, Perth, Western Australia, Australia.³⁵²Department of Public Health, Amrita Institute of Medical Sciences, Kochi, India.³⁵³Department of Clinical Biochemistry, Babol University of Medical Sciences, Babol, Iran.³⁵⁴Golestan University of Medical Sciences, Gorgan, Iran.³⁵⁵Foodborne and Waterborne Diseases Research Center, Shahid Beheshti University of Medical Sciences, Tehran, Iran.³⁵⁶Faculty of General Medicine, Kyrgyz State Medical Academy, Bishkek, Kyrgyzstan.³⁵⁷Department of Atherosclerosis and Coronary Heart Disease, National Center of Cardiology and Internal Disease, Bishkek, Kyrgyzstan.³⁵⁸Health Equity Research Center, Tehran University of Medical Sciences, Tehran, Iran.³⁵⁹Department of Medicine Huddinge, Karolinska Institutet, Stockholm, Sweden.³⁶⁰Department of Food Technology, College of Agriculture, Salahaddin University-Erbil, Erbil, Iraq.³⁶¹Information Technology Department, University of Human Development, Sulaimaniyah, Iraq.³⁶²Department of Biostatistics, Hamadan University of Medical Sciences, Hamadan, Iran.³⁶³School of Pharmacy, Haramaya University, Harar, Ethiopia.³⁶⁴Institute of Public Health, Heidelberg University, Heidelberg, Germany.³⁶⁵Health Systems and Policy Research Unit, Ahmadu Bello University, Zaria, Nigeria.³⁶⁶Faculty of Life Sciences and Medicine, King's College London, London, UK.³⁶⁷Clinical Epidemiology and Public Health Research Unit, Burlo Garofolo Institute for Maternal and Child Health, Trieste, Italy.³⁶⁸Health Sciences Research Center, Mazandaran University of Medical Sciences, Sari, Iran.³⁶⁹Department of Epidemiology and Biostatistics, Kurdistan University of Medical Sciences, Sanandaj, Iran.³⁷⁰Social Determinants of Health Research Center, Kurdistan University of Medical Sciences, Sanandaj, Iran.³⁷¹Department of Epidemiology, Iran University of Medical Sciences, Tehran, Iran.³⁷²Department of Mathematical Sciences, University of Bath,

Bath, UK. ³⁷³International Laboratory for Air Quality and Health, Queensland University of Technology, Brisbane, Queensland, Australia. ³⁷⁴Department of Clinical Biochemistry, Tarbiat Modares University, Tehran, Iran. ³⁷⁵Department of Health Management and Economics, Tehran University of Medical Sciences, Tehran, Iran. ³⁷⁶Federal Institute for Population Research, Wiesbaden, Germany. ³⁷⁷Center for Population and Health, Wiesbaden, Germany. ³⁷⁸Department of Epidemiology and Biostatistics, University of Gondar, Gondar, Ethiopia. ³⁷⁹Department of Pediatric Medicine, Nishtar Medical University, Multan, Pakistan. ³⁸⁰Department of Pediatrics & Pediatric Pulmonology, Institute of Mother & Child Care, Multan, Pakistan. ³⁸¹Department of Urology, Kermanshah University of Medical Sciences, Kermanshah, Iran. ³⁸²Operating Room Department, Kermanshah University of Medical Sciences, Kermanshah, Iran. ³⁸³Research and Analytics, Initiative for Financing Health and Human Development, Chennai, India. ³⁸⁴Research and Analytics, Bioinsilico Technologies, Chennai, India. ³⁸⁵Cancer Research Center of Cancer Institute, Tehran University of Medical Sciences, Tehran, Iran. ³⁸⁶Department of Epidemiology & Biostatistics, Kermanshah University of Medical Sciences, Kermanshah, Iran. ³⁸⁷Suraj Eye Institute, Nagpur, India. ³⁸⁸Cochrane South Africa, South African Medical Research Council, Cape Town, South Africa. ³⁸⁹Emergency Hospital of Bucharest, Carol Davila University of Medicine and Pharmacy, Bucharest, Romania. ³⁹⁰General Surgery Department, Carol Davila University of Medicine and Pharmacy, Bucharest, Romania. ³⁹¹Anatomy and Embryology Department, Carol Davila University of Medicine and Pharmacy, Bucharest, Romania. ³⁹²Department of Cardiology, Cardio-aid, Bucharest, Romania. ³⁹³Department of Biological Sciences, University of Embu, Embu, Kenya. ³⁹⁴Institute for Global Health Innovations, Duy Tan University, Hanoi, Vietnam. ³⁹⁵Center for Excellence in Behavioral Health, Nguyen Tat Thanh University, Ho Chi Minh, Vietnam. ³⁹⁶Global Health Department, University of Washington, Seattle, WA, USA. ³⁹⁷Department of Pediatrics, University of Washington, Seattle, WA, USA. ³⁹⁸Clinical Pharmacy Unit, Mekelle University, Mekelle, Ethiopia. ³⁹⁹Public Health Science Department, School of Public Health and Family Medicine, University of Cape Town, Cape Town, South Africa. ⁴⁰⁰Department of Community and Family Medicine, Iran University of Medical Sciences, Tehran, Iran. ⁴⁰¹University of Social Welfare and Rehabilitation Sciences, Tehran, Iran. ⁴⁰²Department of Health Economics, Tabriz University of Medical Sciences, Tabriz, Iran. ⁴⁰³Department of Medicine, University of Cape Town, Cape Town, South Africa. ⁴⁰⁴Centre of Cardiovascular Research and Education in Therapeutics, Monash University, Melbourne, Victoria, Australia. ⁴⁰⁵Independent Consultant, Accra, Ghana. ⁴⁰⁶Translational Health Research Institute, Western Sydney University, Penrith, New South Wales, Australia. ⁴⁰⁷Center for the Aid Program of Research in South Africa (CAPRISA) TB and HIV Pathogenesis Unit, United Nations Programme on HIV/AIDS (UNAIDS), Durban, South Africa. ⁴⁰⁸Department of Psychiatry and Behavioural Neurosciences, McMaster University, Hamilton, Ontario, Canada. ⁴⁰⁹Department of Psychiatry, University of Lagos, Lagos, Nigeria. ⁴¹⁰Gastroenterology and Liver Disease Research Center, A.C.S. Medical College and Hospital, Tehran, Iran. ⁴¹¹Department of Food Science and Postharvest Technology, Gulu University, Gulu, Uganda. ⁴¹²Ghent University, Ghent, Belgium. ⁴¹³Centre for Healthy Start Initiative, Lagos, Nigeria. ⁴¹⁴Department of Health Promotion and Education, University of Ibadan, Ibadan, Nigeria. ⁴¹⁵Department of Pharmacology and Therapeutics, University of Nigeria Nsukka, Enugu, Nigeria. ⁴¹⁶University of Washington, Seattle, WA, USA. ⁴¹⁷Graduate School of Public Health, San Diego State University, San Diego, CA, USA. ⁴¹⁸Center for Health Systems Research, National Institute of Public Health, Cuernavaca, Mexico. ⁴¹⁹School of Medicine, Autonomous University of Madrid, Madrid, Spain. ⁴²⁰Department of Nephrology and Hypertension, The Institute for Health Research Foundation Jiménez Díaz University Hospital, Madrid, Spain. ⁴²¹Environmental Management and Toxicology, University of Benin, Benin City, Nigeria. ⁴²²Faculty of Geoinformation Science and Earth Observation, University of Twente, Enschede, The Netherlands. ⁴²³Department of Mathematics and Statistics, University of Energy and Natural Resources, Sunyani, Ghana. ⁴²⁴Analytical Center, Moscow Institute of Physics and Technology, Dolgoprudny, Russia. ⁴²⁵Committee for the Comprehensive Assessment of Medical Devices and Information Technology, Health Technology Assessment Association, Moscow, Russia. ⁴²⁶Institute for Advanced Medical Research and Training, University of Ibadan, Ibadan, Nigeria. ⁴²⁷Department of Tb & Respiratory Medicine, Jagadguru Sri Shivarathreeswara University, Mysore, India. ⁴²⁸Department of Medicine, Ottawa Hospital Research Institute, Ottawa, Ontario, Canada. ⁴²⁹Heidelberg University, Heidelberg, Germany. ⁴³⁰Department of Medical Humanities and Social Medicine, Kosin University, Busan, South Korea. ⁴³¹Research and Evaluation, Population Council, New Delhi, India. ⁴³²Indian Institute of Health Management Research University, Jaipur, India. ⁴³³Center for Research and Innovation, Ateneo De Manila University, Pasig City, The Philippines. ⁴³⁴Department of Genetics, Harvard University, Boston, MA, USA. ⁴³⁵Laboratory of Genetics and Molecular Cardiology, University of São Paulo, Sao Paulo, Brazil. ⁴³⁶Department of Cardiology, University of Bern, Bern, Switzerland. ⁴³⁷Parasitology and Entomology Department, Tarbiat Modares University, Tehran, Iran. ⁴³⁸National Centre for Register-Based Research, Aarhus University, Aarhus, Denmark. ⁴³⁹Department of Nutrition and Food Sciences, Maragheh University of Medical Sciences, Maragheh, Iran. ⁴⁴⁰Department of Public Health, Maragheh University of Medical Sciences, Maragheh, Iran. ⁴⁴¹Non-communicable Diseases Research Center, Alborz University of Medical Sciences, Karaj, Iran. ⁴⁴²Biomedical Engineering, Amirkabir University of Technology, Tehran, Iran. ⁴⁴³College of Graduate Health Sciences, A.T. Still University, Mesa, AZ, USA. ⁴⁴⁴Medicchem, Barcelona, Spain. ⁴⁴⁵Molecular and Cell Biology Research Center, Mazandaran University of Medical Sciences, Sari, Iran. ⁴⁴⁶Department of Immunology, Mazandaran University of Medical Sciences, Sari, Iran. ⁴⁴⁷Endocrinology and Metabolism Molecular-Cellular Sciences Institute, Tehran University of Medical Sciences, Tehran, Iran. ⁴⁴⁸Thalassemia and Hemoglobinopathy Research Center, Ahvaz Jundishapur University of Medical Sciences, Ahvaz, Iran. ⁴⁴⁹Department of Clinical Biochemistry, Kermanshah University of Medical Sciences, Kermanshah, Iran. ⁴⁵⁰Sina Trauma and Surgery Research Center, Tehran University of Medical Sciences, Tehran, Iran. ⁴⁵¹Department of Health Education & Promotion, Kermanshah University of Medical Sciences, Kermanshah, Iran. ⁴⁵²Department of Nephrology, Nizam's Institute of Medical Sciences, Hyderabad, India. ⁴⁵³Prevention of Metabolic Disorders Research Center, Shahid Beheshti University of Medical Sciences, Tehran, Iran. ⁴⁵⁴Critical Care Quality Improvement Research Center, Shahid Beheshti University of Medical Sciences, Tehran, Iran. ⁴⁵⁵Policy Research Institute, Kathmandu, Nepal. ⁴⁵⁶Institute for Poverty Alleviation and International Development, Yonsei University, Wonju, South Korea. ⁴⁵⁷Institute of Public Health, Federal University of Bahia, Salvador, Brazil. ⁴⁵⁸Gonçalo Moniz Institute, Oswaldo Cruz Foundation, Salvador, Brazil. ⁴⁵⁹School of Behavioral Sciences and Mental Health, Iran University of Medical Sciences, Tehran, Iran. ⁴⁶⁰Social Science and Psychology, Western Sydney University, Penrith, New South Wales, Australia. ⁴⁶¹School of Social Sciences and Psychology, Western Sydney University, Penrith, New South Wales, Australia. ⁴⁶²Research Center for Environmental Determinants of Health (RCEDH), Kermanshah University of Medical Sciences, Kermanshah, Iran. ⁴⁶³Department of Epidemiology, Shahid Beheshti University of Medical Sciences, Tehran, Iran. ⁴⁶⁴Department of Epidemiology, Birjand University of Medical Sciences, Birjand, Iran. ⁴⁶⁵EPIUnit, University of Porto, Porto, Portugal. ⁴⁶⁶Department of Clinical Research, Federal University of Uberlândia, Uberlândia, Brazil. ⁴⁶⁷Public Health, Addis Ababa University, Addis Ababa, Ethiopia. ⁴⁶⁸Department of Public Health, Wollega University, Nekemte, Ethiopia. ⁴⁶⁹Martin School, University of Oxford, Oxford, UK. ⁴⁷⁰Golestan Research Center of Gastroenterology and Hepatology, Golestan University of Medical Sciences, Gorgan, Iran. ⁴⁷¹Epidemiology and Biostatistics, Kurdistan University of Medical Sciences, Sanandaj, Iran. ⁴⁷²Infectious Diseases and Tropical Medicine Research Center, Babol University of Medical Sciences, Babol, Iran. ⁴⁷³School of Biotechnology, Ikiam Amazon Regional University, Tena, Ecuador. ⁴⁷⁴Department of Ocean Science and Engineering, Southern University of Science and Technology, Shenzhen, China. ⁴⁷⁵Department of Biomedical Sciences, University of Sassari, Sassari, Italy. ⁴⁷⁶Department of Health, Safety and Environment (HSE), Shahid Beheshti University of Medical Sciences, Tehran, Iran. ⁴⁷⁷Faculty of Public Health, Kermanshah University of Medical Sciences, Kermanshah, Iran. ⁴⁷⁸Department of Neuroscience, Iran University of Medical Sciences, Tehran, Iran. ⁴⁷⁹Neurogenic Inflammation Research Center, Mashhad University of Medical Sciences, Mashhad, Iran. ⁴⁸⁰Biotechnology Research Center, Mashhad University of Medical Sciences, Mashhad, Iran. ⁴⁸¹Department of Anatomical Sciences, Kermanshah University of Medical Sciences, Kermanshah, Iran. ⁴⁸²Department of Pathology, Al-Imam Mohammad Ibn Saud Islamic University, Riyadh, Saudi Arabia. ⁴⁸³School of Health and Policy Management, Faculty of Health, York University, Toronto, Ontario, Canada. ⁴⁸⁴Taleghani Hospital, Kermanshah University of Medical Sciences, Kermanshah, Iran. ⁴⁸⁵Department of Radiology and Nuclear Medicine, Kermanshah University of Medical Sciences, Kermanshah, Iran. ⁴⁸⁶Taleghani Hospital, Kermanshah, Iran. ⁴⁸⁷Center for Health Policy & Center for Primary Care and Outcomes Research, Stanford University, Stanford, CA, USA. ⁴⁸⁸Department of Entomology, Ain Shams University, Cairo, Egypt. ⁴⁸⁹Centre School of Public Health and Health Management, University of Belgrade, Belgrade, Serbia. ⁴⁹⁰Post-graduate Program in Infectious Diseases and Tropical Medicine, Federal University of Minas Gerais, Belo Horizonte, Brazil. ⁴⁹¹Department of Community Medicine, PSG Institute of Medical Sciences and Research, Coimbatore, India. ⁴⁹²PSG-FAIMER South Asia Regional Institute, Coimbatore, India. ⁴⁹³Department of Health and Society, Faculty of Medicine, University of Applied and Environmental Sciences, Bogotá, Colombia. ⁴⁹⁴Faculty of Infectious and Tropical Diseases, London School of Hygiene & Tropical Medicine, London, UK. ⁴⁹⁵Surgery Department, Hamad Medical Corporation, Doha, Qatar. ⁴⁹⁶Faculty of Health & Social Sciences, Bournemouth University, Bournemouth, UK. ⁴⁹⁷School of Public Health, Imperial College London, London, UK. ⁴⁹⁸Department of Psychology, University of Alabama at Birmingham, Birmingham, AL, USA. ⁴⁹⁹Center of Expertise in Microbiology, Tehran University of Medical Sciences, Tehran, Iran. ⁵⁰⁰Invasive Fungi Research Center, Mazandaran University of Medical Sciences, Sari, Iran. ⁵⁰¹Department of Health Promotion and Education, Alborz University of Medical Sciences, Karaj, Iran. ⁵⁰²Independent Consultant, Karachi, Pakistan. ⁵⁰³School of Medicine, Dezfoul University of Medical Sciences, Dezfoul, Iran. ⁵⁰⁴Medical Laboratory Sciences, Mazandaran University of Medical Sciences, Sari, Iran. ⁵⁰⁵Chronic Diseases (Home Care) Research Center, Hamadan University of Medical Sciences, Hamadan, Iran. ⁵⁰⁶Department of Laboratory Sciences, Karaj Islamic Azad University, Kermanshah, Iran. ⁵⁰⁷Department of Basic Sciences, Karaj Islamic Azad University, Kermanshah, Iran. ⁵⁰⁸HIV/STI Surveillance Research Center, Kerman University of Medical Sciences, Kerman, Iran. ⁵⁰⁹Policy and Planning Division, Ministry of Health, Riyadh, Saudi Arabia. ⁵¹⁰New University School of Management and Entrepreneurship, Delhi Technological University, New Delhi, India. ⁵¹¹Division of General Internal Medicine and Primary Care, Harvard University, Boston, MA, USA. ⁵¹²Usher Institute of Population Health Sciences and Informatics, University of Edinburgh, Edinburgh, UK. ⁵¹³National Institute of Infectious Diseases, Tokyo, Japan. ⁵¹⁴Finnish Institute of Occupational Health, Helsinki, Finland. ⁵¹⁵Institute of Medical Epidemiology, Martin Luther University Halle-Wittenberg, Halle, Germany. ⁵¹⁶Department of Epidemiology, University of Alabama at Birmingham, Birmingham, AL, USA. ⁵¹⁷Department of Medicine, University of Alabama at Birmingham, Birmingham, AL, USA. ⁵¹⁸Department of Epidemiology, School of Preventive Oncology, Patna, India. ⁵¹⁹Department of Epidemiology, Healis Sekhsaria Institute for Public Health, Mumbai, India. ⁵²⁰Department of Physiotherapy and Occupational Therapy, Næstved-Slagelse-Ringsted Hospitals, Slagelse, Denmark. ⁵²¹Medical Division, German Leprosy and TB Relief Association Ethiopia, Addis Ababa, Ethiopia. ⁵²²Department of Medicine, University of Washington, Seattle, WA, USA. ⁵²³Department of Medicine, University of Calgary, Calgary, Alberta, Canada. ⁵²⁴Social Development and Health Promotion Research Center, Kermanshah University of Medical Sciences, Kermanshah, Iran. ⁵²⁵Hospital Universitario de la Princesa, Autonomous University of Madrid, Madrid, Spain. ⁵²⁶Centro de Investigación en Red de Enfermedades Respiratorias (CIBERES), Institute of Health Carlos III, Madrid, Spain. ⁵²⁷Division of Community Medicine, International Medical University, Kuala Lumpur, Malaysia. ⁵²⁸Department of Nursing, Muhammadiyah University of Surakarta, Kartasura, Indonesia. ⁵²⁹Department of Community Medicine, Ahmadu Bello University, Zaria, Nigeria. ⁵³⁰Department of Criminology, Law and Society, University of California Irvine, Irvine, CA, USA. ⁵³¹Neurology Department, Sree Chitra Tirunal Institute for Medical Sciences and Technology, Trivandrum, India. ⁵³²Carlos III Health Institute, Biomedical Research Networking Center for Mental Health Network (CIBERSAM), Madrid, Spain. ⁵³³Department of Medicine, University of Valencia, Valencia, Spain. ⁵³⁴School of Social Work, University of Illinois, Urbana, IL, USA. ⁵³⁵Cancer Control Center, Osaka International Cancer Institute, Osaka, Japan. ⁵³⁶University Institute 'Egas Moniz', Monte Da Caparica, Portugal. ⁵³⁷Research Institute for Medicines, Faculty of Pharmacy of Lisbon, University of Lisbon, Lisbon, Portugal. ⁵³⁸Department of Pediatrics, King Saud University, Riyadh, Saudi Arabia. ⁵³⁹College of Medicine, Alfaisal University, Riyadh, Saudi Arabia. ⁵⁴⁰Anesthesiology Department, University of

Virginia, Charlottesville, VA, USA. ⁵⁴¹Syrian Expatriate Medical Association (SEMA), Charlottesville, VA, USA. ⁵⁴²Department of Public Health and Community Medicine, Central University Kerala, Kasaragod, India. ⁵⁴³Nanyang Technological University, Singapore, Singapore. ⁵⁴⁴School of Exercise and Nutrition Sciences, Queensland University of Technology, Brisbane, Queensland, Australia. ⁵⁴⁵Department of Pathology and Legal Medicine, University of São Paulo, Sao Paulo, Brazil. ⁵⁴⁶Department of Health Economics, Hanoi Medical University, Hanoi, Vietnam. ⁵⁴⁷Department of Molecular Medicine and Pathology, University of Auckland, Auckland, New Zealand. ⁵⁴⁸Clinical Hematology and Toxicology, Military Medical University, Hanoi, Vietnam. ⁵⁴⁹Gomal Center of Biochemistry and Biotechnology, Gomal University, Dera Ismail Khan, Pakistan. ⁵⁵⁰TB Culture Laboratory, Mufti Mehmood Memorial Teaching Hospital, Dera Ismail Khan, Pakistan. ⁵⁵¹Division of Health Sciences, University of Warwick, Coventry, UK. ⁵⁵²Department of Education and Health, Trauma Research Center, Tehran, Iran. ⁵⁵³Critical and Intensive Care Department, Trauma Research Center, Tehran, Iran. ⁵⁵⁴Argentine Society of Medicine, Buenos Aires, Argentina. ⁵⁵⁵Velez Sarsfield Hospital, Buenos Aires, Argentina. ⁵⁵⁶University Medical Center Groningen, University of Groningen, Groningen, The Netherlands. ⁵⁵⁷Department of General Practice, University Medical Center Groningen, Groningen, The Netherlands. ⁵⁵⁸Ukk Institute, Tampere, Finland. ⁵⁵⁹Psychosocial Injuries Research Center, Ilam University of Medical Sciences, Ilam, Iran. ⁵⁶⁰Raffles Neuroscience Centre, Raffles Hospital, Singapore, Singapore. ⁵⁶¹Yong Loo Lin School of Medicine, National University of Singapore, Singapore, Singapore. ⁵⁶²Department of Medical and Surgical Sciences, University of Bologna, Bologna, Italy. ⁵⁶³Occupational Health Unit, Sant'orsola Malpighi Hospital, Bologna, Italy. ⁵⁶⁴Department of Information Technologies and Management, Moscow Institute of Physics and Technology, Dolgoprudny, Russia. ⁵⁶⁵Department of Information and Internet Technologies, I. M. Sechenov First Moscow State Medical University, Moscow, Russia. ⁵⁶⁶Department of Health Care Administration and Economy, National Research University Higher School of Economics, Moscow, Russia. ⁵⁶⁷Foundation University Medical College, Foundation University, Rawalpindi, Pakistan. ⁵⁶⁸Department of Statistics, University of Washington, Seattle, WA, USA. ⁵⁶⁹Department of Epidemiology and Biostatistics, Wuhan University, Wuhan, China. ⁵⁷⁰Department of Psychiatry, University of São Paulo, Sao Paulo, Brazil. ⁵⁷¹Institute of Child Health, University College London, London, UK. ⁵⁷²Cardiology Department, Royal Children's Hospital, Melbourne, Victoria, Australia. ⁵⁷³Murdoch Childrens Research Institute, Melbourne, Victoria, Australia. ⁵⁷⁴School of Nursing, Aksum University, Aksum, Ethiopia. ⁵⁷⁵Competence Center of Mortality-Follow-Up, Federal Institute for Population Research, Wiesbaden, Germany. ⁵⁷⁶Cochrane South Africa, Medical Research Council South Africa, Cape Town, South Africa. ⁵⁷⁷Department of Global Health, Stellenbosch University, Cape Town, South Africa. ⁵⁷⁸Department of Pharmacology and Toxicology, Mekelle University, Mekelle, Ethiopia. ⁵⁷⁹Department of Pharmacology, Addis Ababa University, Addis Ababa, Ethiopia. ⁵⁸⁰Zhejiang Spine Research Center, Wenzhou Medical University, Wenzhou, China. ⁵⁸¹School of Medicine, Nanjing University, Nanjing, China. ⁵⁸²Department of Diabetes and Metabolic Diseases, University of Tokyo, Tokyo, Japan. ⁵⁸³Department of Health Management, Policy and Economics, Kerman University of Medical Sciences, Kerman, Iran. ⁵⁸⁴Health Services Management Research Center, Kerman University of Medical Sciences, Kerman, Iran. ⁵⁸⁵Department of Pediatrics, University of Jos, Jos, Nigeria. ⁵⁸⁶Department of Pediatrics, Jos University Teaching Hospital, Jos, Nigeria. ⁵⁸⁷Centre for Suicide Research and Prevention, University of Hong Kong, Hong Kong, China. ⁵⁸⁸Department of Social Work and Social Administration, University of Hong Kong, Hong Kong, China. ⁵⁸⁹Department of Psychopharmacology, National Center of Neurology and Psychiatry, Tokyo, Japan. ⁵⁹⁰Health Economics & Finance, Global Health, Jackson State University, Jackson, MS, USA. ⁵⁹¹Research Center for Public Health, Tsinghua University, Peking, China. ⁵⁹²Prevention of Cardiovascular Disease Research Center, Shahid Beheshti University of Medical Sciences, Tehran, Iran. ⁵⁹³Medical Parasitology Department, Cairo University, Cairo, Egypt. ⁵⁹⁴Global Health Institute, Wuhan University, Wuhan, China. ⁵⁹⁵Department of Health Management and Economics, A.C.S. Medical College and Hospital, Tehran, Iran. ⁵⁹⁶Department of Electrical Engineering, Sharif University of Technology, Tehran, Iran. ⁵⁹⁷Electrical Engineering, Institute for Research in Fundamental Sciences, Tehran, Iran. ⁵⁹⁸Social Determinants of Health Research Center, Ardabil University of Medical Science, Ardabil, Iran. ⁵⁹⁹Maternal and Child Health Division, International Centre for Diarrhoeal Disease Research Bangladesh, Dhaka, Bangladesh. ⁶⁰⁰Department of Medicine, Monash University, Melbourne, Victoria, Australia. ⁶⁰¹Student Research Committee, Babol University of Medical Sciences, Babol, Iran. ⁶⁰²Department of Community Medicine, Ardabil University of Medical Science, Ardabil, Iran. ⁶⁰³Social Development and Health Promotion Research Center, Kermanshah University of Medical Sciences, Kermanshah, Iran. ⁶⁰⁴Maternal and Child Wellbeing Unit, African Population Health Research Centre, Nairobi, Kenya. ⁶⁰⁵Public Health Department, Dilla University, Dilla, Ethiopia. ⁶⁰⁶Department of Preventative Medicine, Wuhan University, Wuhan, China. ⁶⁰⁷School of Public Health, Wuhan University of Science and Technology, Wuhan, China. ⁶⁰⁸Indian Institute of Public Health, Public Health Foundation of India, Gurugram, India. ⁶⁰⁹School of BioSciences, University of Melbourne, Parkville, Victoria, Australia. ⁶¹⁰State University of Semarang, Public Health Science Department, Kota Semarang, Indonesia. ⁶¹¹Graduate Institute of Biomedical Informatics, Taipei Medical University, Taipei City, Taiwan. ⁶¹²These authors contributed equally: Roy Burstein, Nathaniel J. Henry. ⁶¹³These authors jointly supervised this work: Christopher J. L. Murray, Simon I. Hay. *e-mail: sihay@uw.edu

METHODS

Overview. We fitted a discrete hazards geostatistical model^{51,52} with correlated space–time–age errors and made predictions to generate joint estimates—with uncertainty—of the probability of death (the number of deaths per live births) and the number of deaths for children aged 0–28 days (neonates), children under 1 year old (infants) and children under 5 years old at the subnational level for 99 LMICs for each year from 2000 to 2017. The analytical process is summarized in the flowchart in Extended Data Fig. 6. We made estimates at a grid-cell resolution of approximately 5×5 -km and then produced spatially aggregated estimates at the first (that is, states or provinces) and second (that is, districts or counties) administrative levels, as well as the country level.

Countries were selected for inclusion in this study based on their socio-demographic index (SDI) published in the Global Burden of Disease study (GBD)⁵³. The SDI is a measure of development based on income per capita, educational attainment and fertility rates among women under 25 years old. We primarily aimed to include all countries in the middle, low–middle or low SDI quintiles, with several exceptions. Brazil and Mexico were excluded despite middle SDI status owing to the availability of high-quality vital registration data in these countries, which have served as the basis for existing subnational estimates of child mortality. Because this study did not incorporate vital registration data sources (see ‘Limitations’), Brazil and Mexico were not estimated directly; instead, state-level estimates from the GBD 2017 study were directly substituted in figures where appropriate⁴. Albania and Moldova were excluded despite middle SDI status owing to geographical discontinuity with other included countries and lack of available survey data. North Korea was excluded despite low–middle SDI status owing to geographical discontinuity and insufficient data. As countries with high–middle SDI status in 2017, China and Malaysia were excluded from this analysis. Libya was included despite high–middle SDI status to create better geographical continuity. Island nations with populations under 1 million were excluded because they typically lacked sufficient survey data or geographical continuity for a geospatial analytic approach to be advantageous over a national approach. Supplementary Figure 3.1 shows a map of the countries included in this study and Supplementary Table 3.1 lists the countries.

Data. We extracted individual records from 555 household sample survey and census sources. Records came in the form of either summary birth histories (SBHs) or complete birth histories (CBHs). All input data were subject to quality checks, which resulted in the exclusion of 82 surveys and censuses owing to quality concerns (see Supplementary Information section 3.2 for more details). Data on life and mortality experiences from CBH sources can be tabulated directly into discrete period and age bins, thus allowing for period-specific mortality estimations, known as the synthetic cohort method^{54–56}. For SBH data, we used indirect estimation⁵⁷ to estimate age-specific mortality probabilities and sample sizes and assign them to specific time periods. Complete details are available in Supplementary Information section 3.3.2.

In all cases, after pre-processing, each data point provided a number of deaths and a sample size for an age bin in a specific year and location. We referenced all data points to GPS coordinates (latitude and longitude) wherever possible. In cases in which GPS data were unavailable, we matched data points to the smallest possible areal unit (also referred to as ‘polygons’). All polygon data were spatially resampled into multiple GPS coordinates and weighted based on the population distribution following a previously described procedure^{5,22,23,58} and described in Supplementary Information section 3.4. Our combined global dataset contained approximately 15.9 million births and 1.1 million child deaths. A complete list of data sources is provided in Supplementary Table 8.1.

In addition to data on child mortality, we used a number of spatial data sources for this analysis. These included a suite of geospatial covariates, population estimates and administrative boundaries⁶⁸. These sources and processing procedures are described in Supplementary Information section 4.

Spatial covariates. We extracted values from each of 10 geospatial covariates at each data point location. Geospatial covariates are spatial data represented at the 5×5 -km grid-cell resolution. The covariates were travel time to the nearest city, educational attainment of maternal-aged women, the ratio of population of children under 5 to women of reproductive age (ages 15–49 years old), the mass per cubic meter of air of particles with a diameter less than $2.5 \mu\text{m}$, total population, a binary indicator of urbanicity, intensity of lights at night, the proportion of children aged 12–23 months who had received the third dose of diphtheria–pertussis–tetanus vaccine, incidence rate of *Plasmodium falciparum*-associated malaria in children under 5 and prevalence of stunting in children under 5 (see Supplementary Information). All covariate values were centred on their means and scaled by their standard deviations. Covariates typically had global spatial coverage and values that vary by year. More details of the spatial covariates can be found in Supplementary Information section 4.

Analysis. *Geostatistical model.* To synthesize information across various sources, and to make consistent estimates across space and time, we fitted discrete hazards^{51,52} geostatistical models⁵⁹ to our data. The models were discrete in the sense

that ages were represented in seven mutually exclusive bins (0, 1–5, 6–11, 12–23, 24–35, 36–47 and 48–59 months), each with its own assumed constant mortality probability. The model explicitly accounted for variation across age bin, year and space through inclusion of both fixed and random effects. Indicator variables for each age bin were included to form a discrete baseline mortality hazard function, representing the risk of mortality in discrete bins from birth to 59 months of age with covariates set at their means. Baseline hazard functions were allowed to vary in space and time in response to changing covariate values, as well as in response to linear effect on year. To model this relationship, we estimated the effect of each covariate value on the risk of mortality. These estimated effects were then applied to the gridded surface of covariate values to make predictions across the entire study geography. We also included a Gaussian random effect across countries to account for larger-scale variations due to political or institutional effects, as well as a Gaussian random effect for each data source to account for source-specific biases. Finally, we included a Gaussian process random effect with a covariance matrix structured to account for remaining correlation across age, time and physical space. As such, estimates at a specific age, time or place benefited from drawing predictive strength from data points nearby in all of these dimensions.

For each modelling region, we fitted one such discrete hazards model with a binomial data likelihood. All data were prepared such that we counted or estimated the number of children entering into (n) and dying within (Y) each period–age bin from each GPS-point location (s) in each survey (k) within each country (c).

The number of deaths for children in age band (a) in year (t) at location (s) was assumed to follow a binomial distribution:

$$Y_{a,s,t} \sim \text{binomial}(n_{a,s,t}, P_{a,s,t})$$

where $P_{a,s,t}$ is the probability of death in age bin a , conditional on survival to that age bin for a particular space–time location. Using a generalized linear regression modelling framework, a logit link function is used to relate P to a linear combination of effects:

$$\text{logit}(P_{a,s,t}) = \beta^0 + \sum_{a=2}^7 I_a \beta_a^1 + \beta^2 X_{s,t} + \beta^3 t + \nu_{c[s]} + \nu_{k[s]} + Z_{a,s,t}$$

The first term, β^0 , is an intercept, representing the mean for the first age band when all covariates are equal to zero, whereas β_a^1 are fixed effects for each age band, representing the mean overall hazard deviation for each age band from the intercept, when all other covariates are equal to zero. β^2 are the effects of geospatial covariates ($X_{s,t}$), which we describe in detail in Supplementary Information section 4. β^3 is an overall linear temporal effect to account for overall temporal trends within the region. All geospatial covariates were centred and scaled by subtracting their mean and dividing by their standard deviations. Each ν term represents uncorrelated Gaussian random effects: $\nu_{c[s]} \sim \text{normal}(0, \sigma_c^2)$ is a country-level random effect applied to all locations (s) within a country (c); $\nu_{k[s]} \sim \text{normal}(0, \sigma_k^2)$ is a data source-level random effect for the survey (k) from which the data at location s were observed. Data source-level random effects were used to account for systematic variation or biases across data sources and were included in model fitting but not in prediction from fitted models. The term $Z_{a,s,t} \sim \text{Gaussian process}(0, K)$ is a correlated random effect across age, space and time, and is modelled as a four-dimensional mean zero Gaussian process with covariance matrix K . This term accounts for structured residual correlation across these spatial–age–temporal dimensions that are not accounted for by any of the model’s other fixed or random effects. This structure was chosen, because the hazard probability for each age group is expected to vary in space and time, and such spatiotemporal correlations are likely to be similar across ages. K is constructed as a separable process across age, space and time ($K = \Sigma_a \otimes \Sigma_t \otimes \Sigma_s$). The continuous spatial component is modelled with a stationary isotropic Matérn covariance function, and the age and temporal effects were each assumed to be discrete auto-regressive order 1. We provide further details on model fitting and specification in Supplementary Information section 5.1.

We assigned priors to all model parameters and performed maximum a posteriori inference using Template Model Builder⁶⁰ software in R version 3.4. We fitted the model separately for each of 11 world regions (see Supplementary Fig. 3.1), owing to memory constraints and to allow model parameters to vary across epidemiologically distinct regions.

Post-estimation. Using the joint precision matrix and point estimates, we generated 1,000 draws from all model parameters using a multivariate-normal approximation. These model parameter draws were used to predict corresponding draws of mortality probabilities across all age groups for each grid cell in each year. In other words, for each age bin in each year we estimated 1,000 gridded surfaces of mortality probability estimates, each surface corresponding to one draw from the posterior parameter estimates⁶¹. All subsequent post-estimation procedures were carried out across draws to propagate model uncertainty. We used these estimated

spatiotemporal gridded surfaces of age-specific mortality probabilities to produce various final resulting data products.

From the fitted model parameters, we produced posterior mortality probability estimates for each age group for each 5×5 -km grid cell for each year from 2000 to 2017. We combined gridded age group estimates to obtain infant (under 1) and child (under 5) mortality estimates at each gridded location. Using a conversion from mortality probability to mortality rates, and using a gridded surface of population, we also estimated the number of deaths that occurred in each age group at each location in each year. For both mortality probabilities and counts, we multiplied out corresponding gridded estimates by a constant to ensure that at the national—and in two countries, the first administrative-level unit—aggregated estimates for each age group and year were calibrated such that they equalled estimates in the GBD study⁴. This calibration allowed us to take advantage of national data sources, such as vital registration, that could not be used in this study. We also aggregated grid-cell-level estimates to first and second administrative-level units using gridded population surface to weight estimates. These steps are described in Supplementary Information section 5.2.

Model validation. We used fivefold cross-validation to assess and compare model performance with respect to estimating local trends of age-specific mortality. Each fold was created by combining complete surveys into subsets of approximately 20% of data sources from the input data. Holding out entire surveys at a time served as a comparable approximation to the type of missingness in our data, essentially helping us check how well our model estimates of mortality probabilities compared to empirical estimates of mortality probability from an unobserved data source that did not inform the model.

For each posterior draw, we aggregated to administrative units. Using data aggregated to the administrative unit and aggregated estimate pairs, we calculated the difference between out-of-sample empirical data estimates and modelled estimates, and we report the following summary metrics: mean error, which serves as a measure of bias, the square root of mean errors, which serves as a measure of the total variation in the errors, the correlation and 95% coverage. At the second administrative-level unit for under-5 mortality, our out-of-sample 95% coverage was 93%, correlation was 0.78, mean absolute error was 0.015 and mean error was -0.0011 . These results indicate a good overall fit, with minimal bias. This procedure and the full validation results are discussed in Supplementary Information section 5.3.

Limitations. This work should be assessed in full acknowledgement of several data and methodological limitations. We exclusively used CBH and SBH data from household survey and census data sources. Ideally, estimates of child mortality should incorporate all available data, including data from administrative vital registration systems. Vital registration systems are commonly present in many middle-income and all high-income countries. There are known data-quality issues with vital registration sources in many middle-income countries^{48,62} that add complications to their inclusion in our modelling procedure. For example, systems may not capture all deaths, and this level of ‘underreporting’ probably varies in space, time and age. In addition, underreporting is probably negatively correlated with mortality, and could contribute substantial bias to estimates. Statistical methods must be developed to jointly estimate—and adjust for—underreporting in vital registration data before such data can be used in geospatial models of child mortality. Promising work has begun in this domain in specific countries⁶³, but further advancement will be necessary to improve estimates across a time series and across many countries at once.

We assume that SBH and CBH data were retrospectively representative in the locations in which they were collected. As such, we assume that survey respondents did not migrate. High-spatial-resolution migration estimates with which to adjust estimates do not yet exist, and many of the data sources that we use do not collect information on migration. We conducted a focused sensitivity analysis (Supplementary Information section 5.4.4) for migration in six countries, and found that although our results were generally robust, there was variation by country. Furthermore, despite providing high-quality retrospective data from representative samples of households, birth history data can suffer from certain non-sampling issues, such as survival/selection biases⁶⁴ and misplacement of births⁶⁵. We did not attempt to make corrections to data, and they were used as-is. Furthermore, retrospective birth history data will—by design—have a changing composition of maternal ages depending on the time since the survey. This was minimized by limiting retrospective trends to up to 17 years.

Although we collated a large geo-referenced database of survey data on child mortality, these data represented about 1% (1.1 million) of total deaths of children under 5 in study areas over the period. Where data do not exist or are not available in certain locations, mean estimates are informed from smoothing to nearby estimates and covariates. As such, there could be additional small-scale heterogeneity that is not picked up by our model. Wider uncertainty intervals in areas with no data account for these potential unknowns, and our 95% coverage estimates in out-of-sample predictive tests appear to be well-calibrated at the second

administrative unit level. Furthermore, discrete localized mortality shock events could be missing in our analysis due to the lack of data and selection biases in surveys and censuses, and spatiotemporal smoothing. Fatal discontinuities are explicitly accounted for at the national or province level by calibration to GBD estimates. In all, 0.35% (0.4 million) of the 123 million deaths over this period were attributed to fatal discontinuities.

On the modelling side, we integrated point and areal data into a continuous model by constructing pseudo-points from areal data. Modelling approaches that integrate point and areal data as part of a joint model likelihood function are in development⁶⁶ but are currently computationally infeasible at the large geographical scales at which we currently model. Furthermore, we divided our models into 11 regional fits (see Supplementary Fig. 3.1), as a full model that encompasses all 99 countries would be computationally infeasible due to memory constraints. Splitting up modelling in this way had the benefit of enabling parameters to vary across epidemiologically distinct world regions. A preferred model, however, would be fitted to all data simultaneously with parameters that are spatially variable.

The separable model used for age–space–time correlations is a common parsimonious assumption afforded in applying spatiotemporal geostatistical models due to efficient computation and inference; however, it yields the assumption of fully symmetric covariance. The symmetry implicit in the separable model dictates, for example, that (holding age constant for simplicity) the covariance between the observations at (location 1, time 1) and (location 2, time 2) is the same as the covariance between (location 1, time 2) and (location 2, time 1). Given our available data density in space–age–time, we believe that attempting to parameterize a more complex non-separable model would be challenging both computationally and inferentially, and it is not clear whether there would be much to benefit from the extra complications.

There are several limitations to address with respect to the use of covariates in the model. Most of the geospatial covariates that we used in the geostatistical model were themselves estimates produced from various geospatial models. Some of those estimated surfaces used covariates that were also included in our model in their estimation process. As such, we emphasize that our model is meant to be predictive, and that drawing inference from fitted coefficients across these highly correlated covariates is problematic and not recommended. Furthermore, we assumed no measurement error in the covariate values and assumed that the functional form between mortality and all covariates was linear in logit space. In certain locations, we used covariate values for prediction that were outside the observed range of the training data. As we explore in Supplementary Information section 5.4.2, however, these areas represent a relatively small proportion of the population.

Finally, we used a method for indirect estimation of SBHs that was recently developed and validated⁵⁷. As such, indirect estimation was carried out as a pre-processing step before fitting the geostatistical model. We attempted to propagate various forms of uncertainty that could be introduced in this step, which resulted in halving the total effective sample size across all SBH data. In future, we aim to fully integrate such processing into the statistical model; such methods are in development⁶⁷, but are not yet computationally feasible at scale.

Reporting summary. Further information on research design is available in the Nature Research Reporting Summary linked to this paper.

Data availability

The findings of this study are supported by data that are available from public online repositories, data that are publicly available upon request of the data provider and data that are not publicly available due to restrictions by the data provider. Non-publicly available data were used under a license for the current study, but may be available from the authors upon reasonable request and with permission of the data provider. A detailed table of data sources and availability can be found in Supplementary Table 8.1. The full output of the analyses is publicly available in the Global Health Data Exchange (GHDx; <http://ghdx.healthdata.org/record/ihme-data/lmic-under5-mortality-rate-geospatial-estimates-2000-2017>) and can be explored using custom data visualization tools (<https://vizhub.healthdata.org/lbd/under5>).

- Lindgren, F., Rue, H. & Lindström, J. An explicit link between Gaussian fields and Gaussian Markov random fields: the stochastic partial differential equation approach. *R. Stat. Soc.* **73**, 423–498 (2011).
- Allison, P. D. Discrete-time methods for the analysis of event histories. *Sociol. Methodol.* **13**, 61 (1982).
- Institute for Health Metrics and Evaluation. *Global Burden of Disease Study 2017 (GBD 2017) Socio-Demographic Index (SDI) 1950–2017*. <http://ghdx.healthdata.org/record/ihme-data/gbd-2017-socio-demographic-index-sdi-1950%E2%80%932017> (GHDx, 2019).
- Ahmad, O. B., Lopez, A. D. & Inoue, M. The decline in child mortality: a reappraisal. *Bull. World Health Organ.* **78**, 1175–1191 (2000).
- Somoza, J. L. *Illustrative Analysis: Infant and Child Mortality in Colombia*. *World Fertility Survey Scientific Report No. 10* (International Statistical Institute, 1980).

56. Rutstein, S. O. *Infant and child mortality: levels, trends and demographic differentials. World Fertility Survey Scientific Report No. 43* (International Statistical Institute, 1984).
57. Burstein, R., Wang, H., Reiner, R. C. Jr & Hay, S. I. Development and validation of a new method for indirect estimation of neonatal, infant, and child mortality trends using summary birth histories. *PLoS Med.* **15**, e1002687 (2018).
58. Graetz, N. et al. Mapping local variation in educational attainment across Africa. *Nature* **555**, 48–53 (2018).
59. Diggle, P. & Ribeiro, P. J. *Model-based Geostatistics* (Springer, 2007).
60. Kristensen, K., Nielsen, A., Berg, C. W., Skaug, H. & Bell, B. M. TMB: automatic differentiation and Laplace approximation. *J. Stat. Softw.* **70**, 1–21 (2016).
61. Patil, A. P., Gething, P. W., Piel, F. B. & Hay, S. I. Bayesian geostatistics in health cartography: the perspective of malaria. *Trends Parasitol.* **27**, 246–253 (2011).
62. Phillips, D. E. et al. A composite metric for assessing data on mortality and causes of death: the vital statistics performance index. *Popul. Health Metr.* **12**, 14 (2014).
63. Schmettmann, C. P. & Gonzaga, M. R. Bayesian estimation of age-specific mortality and life expectancy for small areas with defective vital records. *Demography* **55**, 1363–1388 (2018).
64. Walker, N., Hill, K. & Zhao, F. Child mortality estimation: methods used to adjust for bias due to AIDS in estimating trends in under-five mortality. *PLoS Med.* **9**, e1001298 (2012).
65. Silva, R. Child mortality estimation: consistency of under-five mortality rate estimates using full birth histories and summary birth histories. *PLoS Med.* **9**, e1001296 (2012).
66. Wilson, K. & Wakefield, J. Pointless spatial modeling. *Biostatistics* <https://doi.org/10.1093/biostatistics/kxy041> (2018).
67. Wilson, K. & Wakefield, J. Child mortality estimation incorporating summary birth history data. Preprint at <https://arxiv.org/abs/1810.04140> (2018).
68. WorldPop Dataset (WorldPop, accessed 25 July 2017); http://www.worldpop.org.uk/data/get_data/

Acknowledgements This work was primarily supported by grant OPP1132415 from the Bill & Melinda Gates Foundation.

Author contributions S.I.H. and R.B. conceived and planned the study. R.B., S.I.H., M.C., N.H., J.L., A.B., N.G. and S.W. identified and obtained data for this analysis. M.C., N.H., J.L., A.B. and S.W. extracted, processed and geo-positioned the data. R.B. and N.H. carried out the statistical analyses with assistance and input from S.I.H., A.O.-Z. and N.M. R.B., N.H., M.C., S.W., L.W., K.J. and L.E. prepared figures and tables. R.B. and L.B.M. wrote the first draft of the manuscript with assistance from S.I.H., S.P., L.E.S. and N.D.W. and all authors contributed to subsequent revisions. All authors provided intellectual input into aspects of this study.

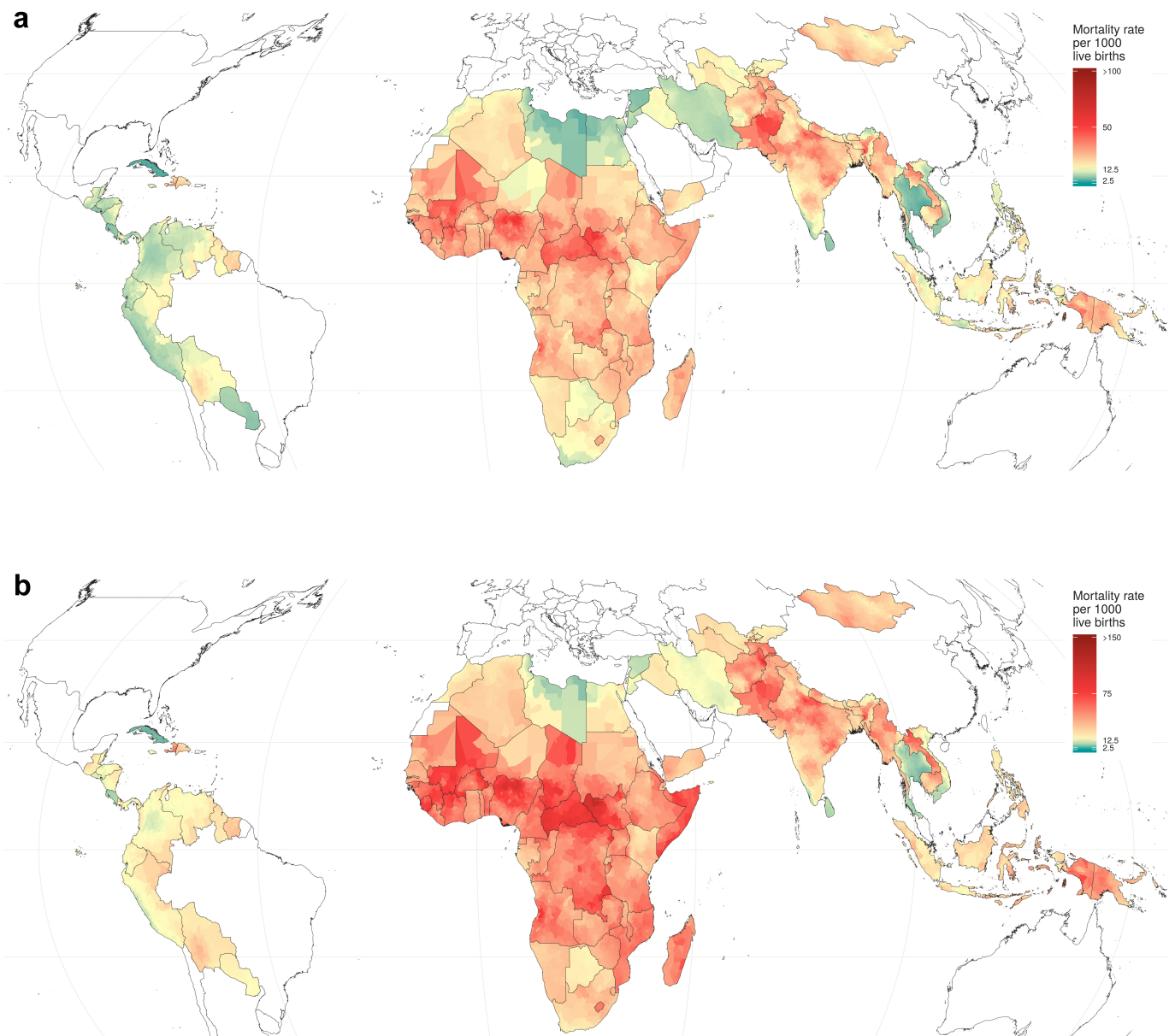
Competing interests This study was funded by the Bill & Melinda Gates Foundation. Co-authors employed by the Bill & Melinda Gates Foundation provided feedback on initial maps and drafts of this manuscript. Otherwise, the funders of the study had no role in study design, data collection, data analysis, data interpretation, writing of the final report, or decision to publish. The corresponding author had full access to all of the data in the study and had final responsibility for the decision to submit for publication.

Additional information

Supplementary information is available for this paper at <https://doi.org/10.1038/s41586-019-1545-0>.

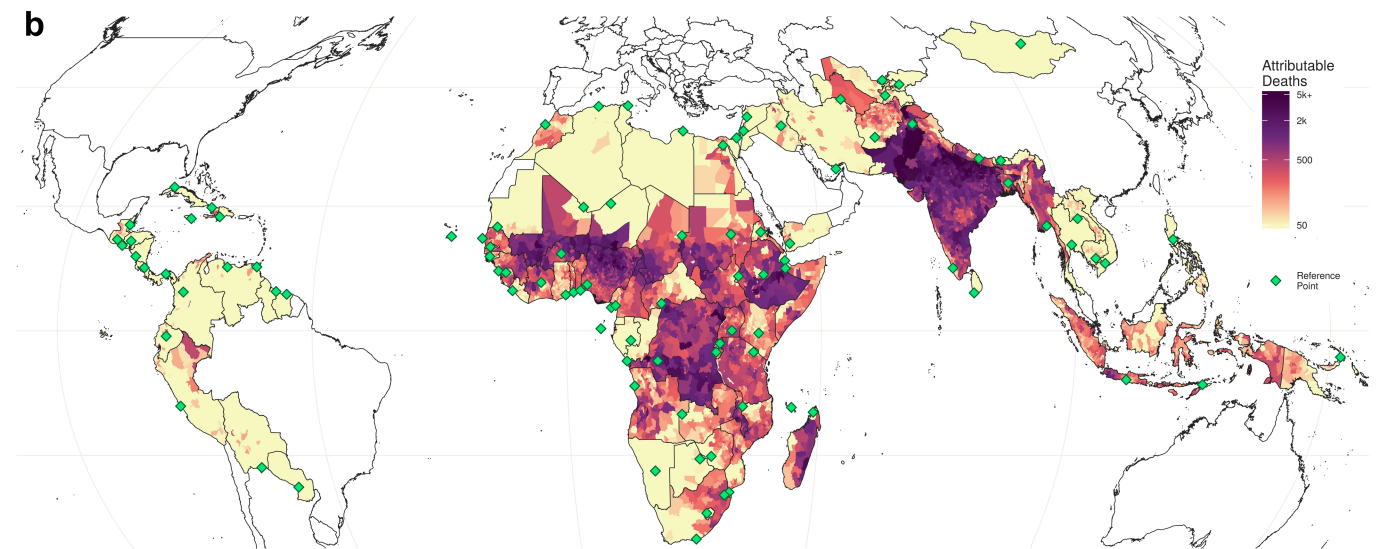
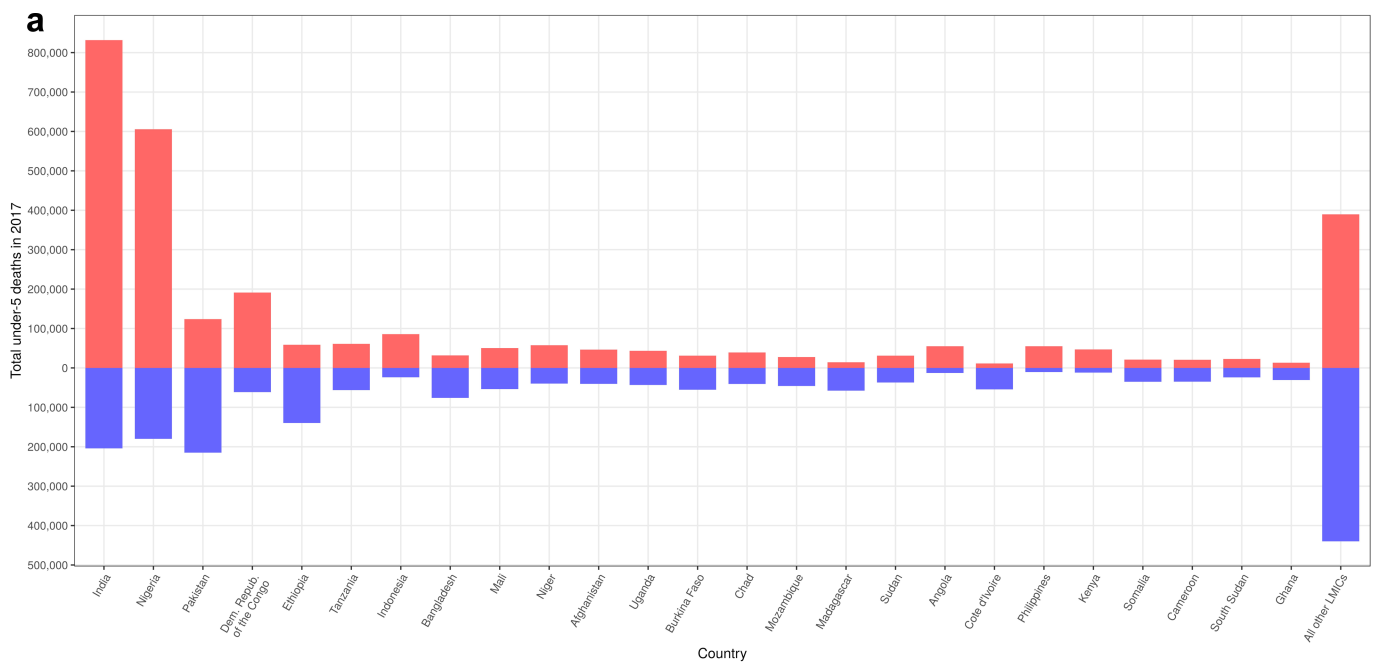
Correspondence and requests for materials should be addressed to S.I.H.

Peer review information *Nature* thanks Paloma Botella and the other, anonymous, reviewer(s) for their contribution to the peer review of this work. **Reprints and permissions information** is available at <http://www.nature.com/reprints>.



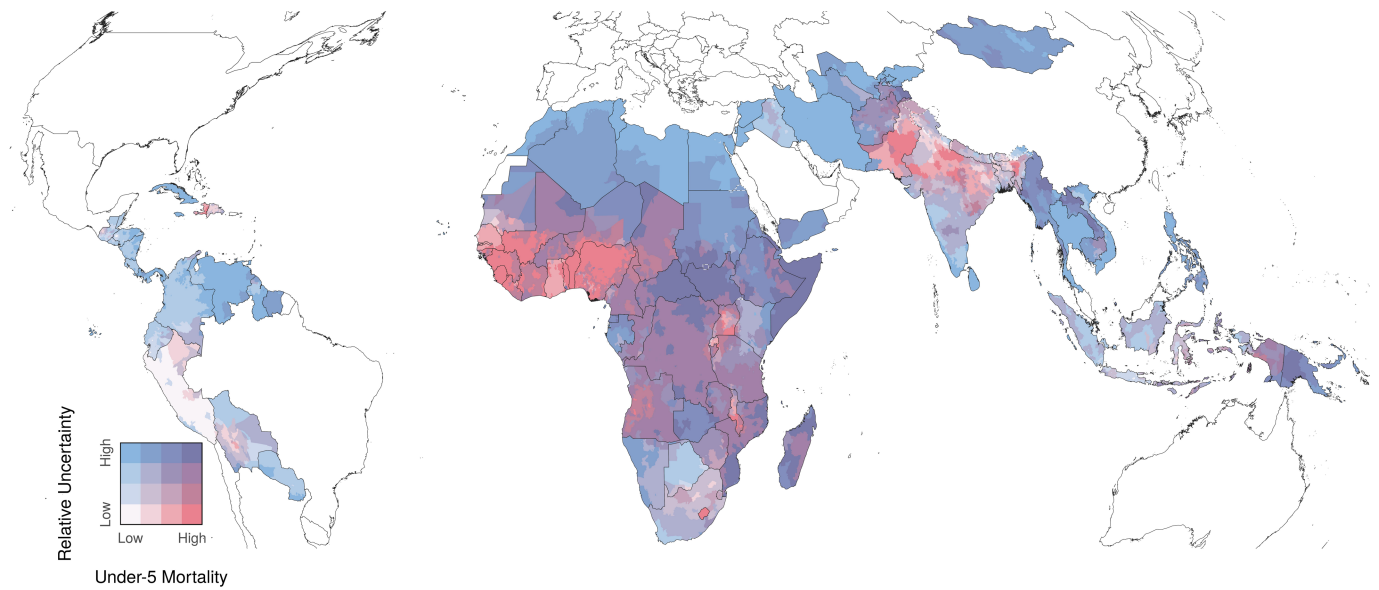
Extended Data Fig. 1 | Neonatal and infant mortality rates in 2017.
a, b, Maps showing the mortality rates of neonates (**a**; birth to 28 days of age) and infants (**b**; under 1 year of age) across second administrative-level

units in 2017. Note that the ranges in the keys are different for the two maps.



Extended Data Fig. 2 | Impact of inequality on U5MR. a, Potential reduction in the number of deaths that would have occurred if all second administrative-level units in the 20 countries with the greatest number of deaths of children under 5 in 2017 realized a homogenous U5MR that was equal to that of the lowest observed mortality rate in that country. In total, 66% of under-5 deaths could have been averted if all countries maintained mortality rates equal to the second administrative-level unit with lowest mortality. If this reference rate is set to the lowest observed rate across all of the 99 countries that were included in this study, 95% of under-5 deaths could have been averted. The size of each bar represents the total number

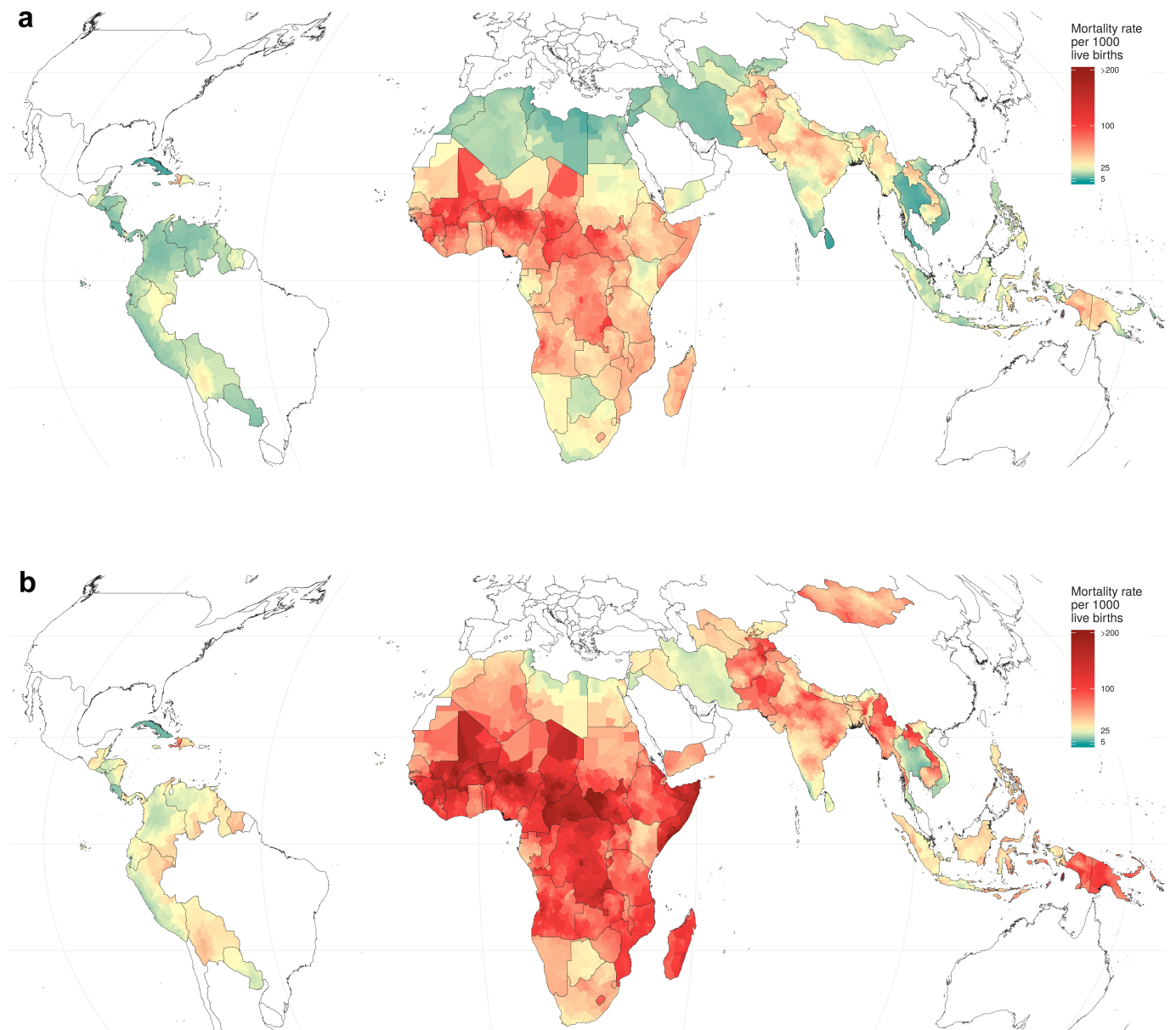
of under-5 deaths in each country. The red portion of each bar indicates the number of deaths 'attributed' to geographical inequality in mortality rates, whereas the blue portion represents the number of deaths that would remain in the scenario in which all second administrative-level units within countries had the same mortality rate as the best-performing unit. **b,** Locations of under-5 deaths 'attributable' to geographical inequality, across all second administrative-level units in each country. Each country has one unit highlighted with a green diamond, which is the reference unit, or the location with the lowest mortality rate in the country in 2017.



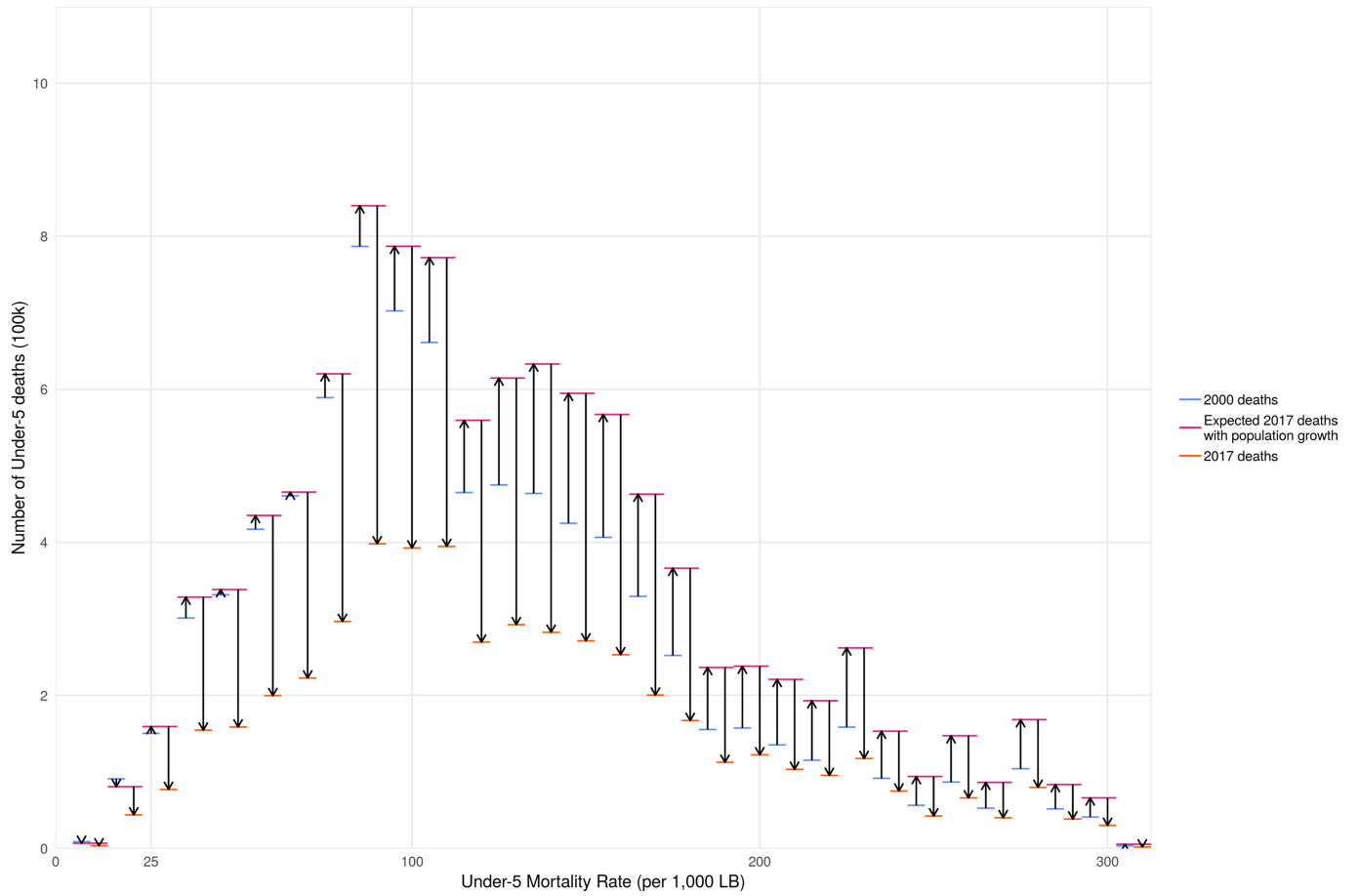
Extended Data Fig. 3 | Relative uncertainty in U5MR estimates for 2017.

Relative uncertainty in second administrative-level estimates compared with mean estimated U5MRs in each second administrative-level unit for 2017. Mean rates and relative uncertainty are split into population-weighted quartiles. These cut-off points indicate the relative uncertainty minimum, 25th, 50th and 75th percentiles, and maximum, which are 0.29, 0.51, 0.63 and 0.86, and 3.12, respectively. The under-5 mortality minimum, 25th, 50th and 75th percentiles, and maximum are 1.4, 13.0,

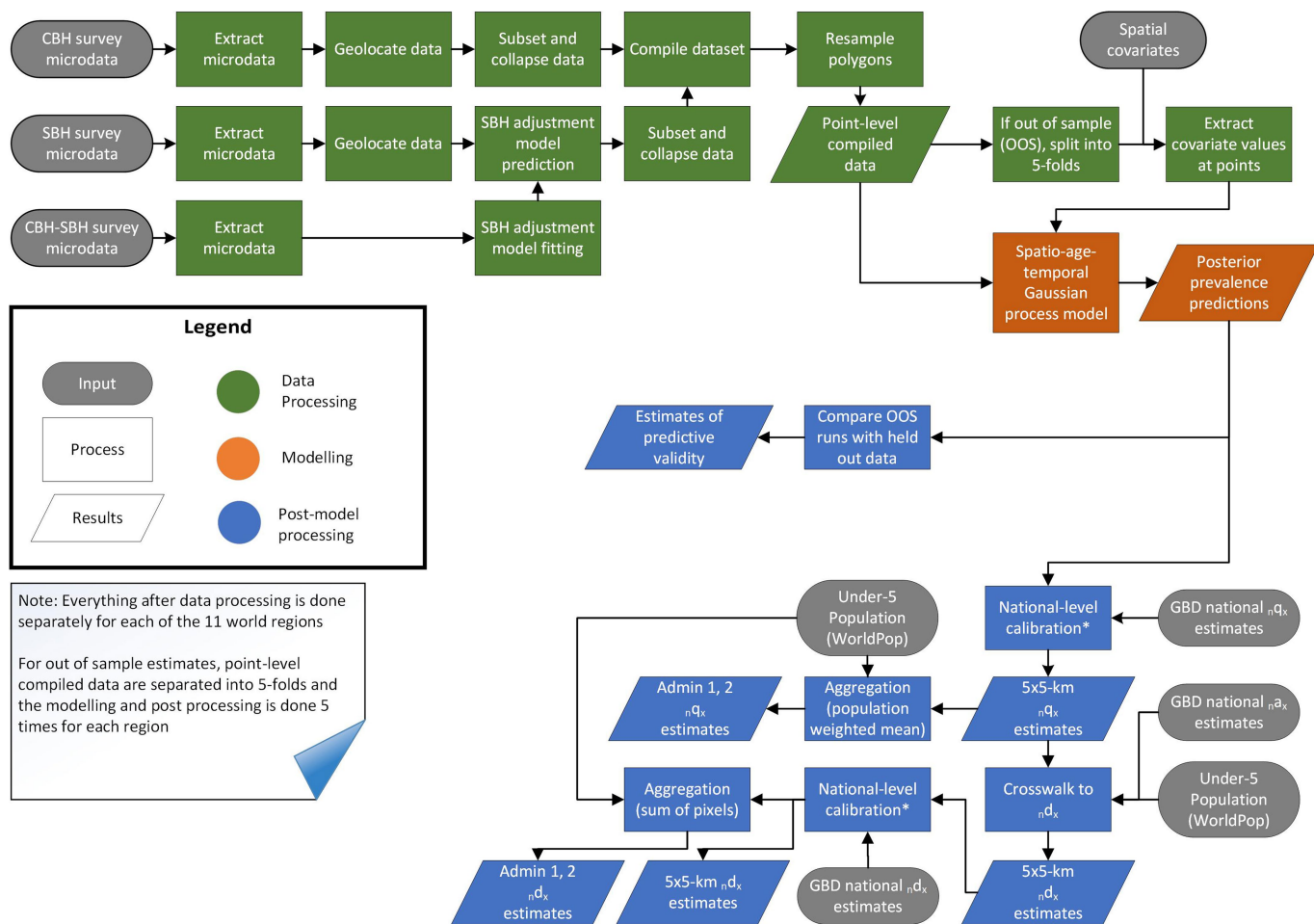
22.9 and 44.8, and 190.6 deaths per 1,000 live births. Areas in which our estimates are more uncertain are coloured with a scale of increasing blue hue, whereas areas in which the mean estimates of U5MR are high are coloured with a scale of increasing red hue. Purple areas have high, but uncertain, estimates of U5MRs. White areas have low relative mortality, with fairly certain estimates. Relative uncertainty is defined as the ratio of the width of the 95% uncertainty interval to the mean estimate.



Extended Data Fig. 4 | Lower and upper uncertainty interval boundaries for U5MR mortality estimates in 2017. a, b, Lower (a) and upper (b) 95% uncertainty intervals for U5MR estimates across the second administrative-level units in 99 countries.



Extended Data Fig. 5 | The counteracting forces of population change and mortality rate decline on total number of under-5 deaths. Arrow plots show the mortality rate strata (bins of 10 per 1,000 livebirths) in 2000.



Extended Data Fig. 6 | Flowchart summarizing analytical process. Standard demographic notation were used. n , length of age bin; x , starting age of age bin; d , number of deaths; q , probability of death; a , average time lived in age bin by those who died in the age bin.

Reporting Summary

Nature Research wishes to improve the reproducibility of the work that we publish. This form provides structure for consistency and transparency in reporting. For further information on Nature Research policies, see [Authors & Referees](#) and the [Editorial Policy Checklist](#).

Statistics

For all statistical analyses, confirm that the following items are present in the figure legend, table legend, main text, or Methods section.

n/a Confirmed

- The exact sample size (n) for each experimental group/condition, given as a discrete number and unit of measurement
- A statement on whether measurements were taken from distinct samples or whether the same sample was measured repeatedly
- The statistical test(s) used AND whether they are one- or two-sided
Only common tests should be described solely by name; describe more complex techniques in the Methods section.
- A description of all covariates tested
- A description of any assumptions or corrections, such as tests of normality and adjustment for multiple comparisons
- A full description of the statistical parameters including central tendency (e.g. means) or other basic estimates (e.g. regression coefficient) AND variation (e.g. standard deviation) or associated estimates of uncertainty (e.g. confidence intervals)
- For null hypothesis testing, the test statistic (e.g. F , t , r) with confidence intervals, effect sizes, degrees of freedom and P value noted
Give P values as exact values whenever suitable.
- For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings
- For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes
- Estimates of effect sizes (e.g. Cohen's d , Pearson's r), indicating how they were calculated

Our web collection on [statistics for biologists](#) contains articles on many of the points above.

Software and code

Policy information about [availability of computer code](#)

Data collection

No primary data collection was carried out for this analysis.

Data analysis

This analysis was carried out using R version 3.5.0. The main statistical model used the Template Model Builder (TMB) software version 1.7.14 in R. All code used for these analyses is publicly available online at <https://github.com/ihmeuw/lbd/tree/u5mr-2019>.

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors/reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Research [guidelines for submitting code & software](#) for further information.

Data

Policy information about [availability of data](#)

All manuscripts must include a [data availability statement](#). This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
- A list of figures that have associated raw data
- A description of any restrictions on data availability

The findings of this study are supported by data available in public online repositories, data publicly available upon request of the data provider, and data not publicly available due to restrictions by the data provider. Non-publicly available data were used under license for the current study but may be available from the authors upon reasonable request and with permission of the data provider. A detailed table of data sources and availability can be found in Supplementary Table 8.1. The full output of the analyses are publicly available in the Global Health Data Exchange (<http://ghdx.healthdata.org/>) and can further be explored via data visualization tools (<https://healthdata.org/lbd/under5>).

Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

Life sciences Behavioural & social sciences Ecological, evolutionary & environmental sciences

For a reference copy of the document with all sections, see [nature.com/documents/nr-reporting-summary-flat.pdf](https://www.nature.com/documents/nr-reporting-summary-flat.pdf)

Life sciences study design

All studies must disclose on these points even when the disclosure is negative.

Sample size	This observational study incorporated all available survey data sources that met the inclusion criteria as described in the Methods section. The combined dataset used in this analysis contained 25.1 million births and 1.3 million child deaths.
Data exclusions	Surveys were excluded due to missingness greater than 10% in date of birth or death and children ever born or died, unrealistic geographic trends compared to other surveys in nearby country-years, inability to match the microdata to geographic locations, or non-standard methodology. A full list of excluded surveys is included in Supplementary Table 8.2.
Replication	This is an observational study using many years of survey and surveillance data and could be replicated.
Randomization	This analysis is an observational mapping study, there were no experimental groups.
Blinding	Blinding was not relevant to this study, as it was an observational study using survey and surveillance data.

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study
<input checked="" type="checkbox"/>	<input type="checkbox"/> Antibodies
<input checked="" type="checkbox"/>	<input type="checkbox"/> Eukaryotic cell lines
<input checked="" type="checkbox"/>	<input type="checkbox"/> Palaeontology
<input checked="" type="checkbox"/>	<input type="checkbox"/> Animals and other organisms
<input checked="" type="checkbox"/>	<input type="checkbox"/> Human research participants
<input checked="" type="checkbox"/>	<input type="checkbox"/> Clinical data

Methods

n/a	Involved in the study
<input checked="" type="checkbox"/>	<input type="checkbox"/> ChIP-seq
<input checked="" type="checkbox"/>	<input type="checkbox"/> Flow cytometry
<input checked="" type="checkbox"/>	<input type="checkbox"/> MRI-based neuroimaging