Sources of variation in under-5 mortality across sub-Saharan Africa: a spatial analysis

Marshall Burke, Sam Heft-Neal, Eran Bendavid

Summary

Background Detailed spatial understanding of levels and trends in under-5 mortality is needed to improve the targeting of interventions to the areas of highest need, and to understand the sources of variation in mortality. To improve this understanding, we analysed local-level information on child mortality across sub-Saharan Africa between 1980–2010.

Methods We used data from 82 Demographic and Health Surveys in 28 sub-Saharan African countries, including the location and timing of 3·24 million childbirths and 393 685 deaths, to develop high-resolution spatial maps of under-5 mortality in the 1980s, 1990s, and 2000s. These estimates were at a resolution of 0·1 degree latitude by 0·1 degree longitude (roughly 10 km×10 km). We then analysed this spatial information to distinguish within-country versus between-country sources of variation in mortality, to examine the extent to which declines in mortality have been accompanied by convergence in the distribution of mortality, and to study localised drivers of mortality differences, including temperature, malaria burden, and conflict.

Findings In our sample of sub-Saharan African countries from the 1980s to the 2000s, within-country differences in under-5 mortality accounted for 74–78% of overall variation in under-5 mortality across space and over time. Mortality differed significantly across only 8–15% of country borders, supporting the role of local, rather than national, factors in driving mortality patterns. We found that by the end of the study period, 23% of the eligible children in the study countries continue to live in mortality hotspots—areas where, if current trends continue, the Sustainable Developent Goals mortality targets will not be met. In multivariate analysis, within-country mortality levels at each pixel were significantly related to local temperature, malaria burden, and recent history of conflict.

Interpretation Our findings suggest that sub-national determinants explain a greater portion of under-5 mortality than do country-level characteristics. Sub-national measures of child mortality could provide a more accurate, and potentially more actionable, portrayal of where and why children are still dying than can national statistics.

Funding The Stanford Woods Institute for the Environment.

Lancet Glob Health 2016; 4: e936–45

Published Online October 25, 2016 http://dx.doi.org/10.1016/S2214-109X(16)30212-1

See Comment page e877

Department of Earth System Science (M Burke PhD, S Heft-Neal PhD), **Center on Food Security and the Environment** (M Burke), **and Division of General Medical Disciplines, Center for Health Policy, and the Center for Primary Care and Outcomes Research** (E Bendavid MD), **Stanford University, Stanford, CA, USA; and National Bureau of Economic Research, Cambridge, MA, USA** (M Burke)

Correspondence to: Dr Eran Bendavid, Division of General Medical Disciplines, Center for Health Policy, and the Center for Primary Care and Outcomes Research, Stanford University, Stanford, CA 94305, USA **ebd@stanford.edu**

Introduction

The ongoing decline in under-5 mortality ranks among the most significant public and population health successes of the past 30 years. Deaths of children under the age of 5 years have fallen from nearly 13 million per year in 1990 to less than 6 million per year in 2015, even as the world's under-5 population grew by nearly 100 million children.[1–3] However, the amount of variability underlying this broad global progress is substantial. On a regional level, east Asia and the Pacific have surpassed the Millennium Development Goal target of a two-thirds reduction in under-5 mortality rate between 1990 and 2015, whereas sub-Saharan Africa has had only a 24% decline over the same period. Large differences in progress are also evident within sub-Saharan Africa, where mortality rates have declined by more than 70% from 1990 to 2015 in some countries and increased in others; in 2015, the mortality rate in some countries was more than three times that in others.[3–6]

What explains this remarkable variation in progress against under-5 mortality? Answering this question requires understanding of where the main sources of variation in mortality lie. One view that is implicit in the way that mortality rates are tracked and targeted is that national policies and conditions drive first-order changes in under-5 mortality.[6] This country-level focus is justified by research that emphasises the role of institutional factors in explaining variation in mortality—factors such as universal health coverage, women's education, and the effectiveness of national health systems.[7–9] It is argued that these factors, which vary measurably at the country level, fundamentally shape the ability of individuals and communities to affect more proximate causes of child death such as malaria and diarrhoeal disease.

An alternate view has focused on exploring the importance of subnational variation in the distribution of disease. In the USA, studies on the geographical distribution of health care and mortality have been influential for targeting of resources and policy design.[10–12] Similar studies in developing regions have shown the substantial variability in the distribution and changes of important health outcomes such HIV, malaria, and schistosomiasis—information that can

Research in context

Evidence before this study

Measurement and monitoring of under-5 mortality is a global priority and an important indicator of development. Of all the world's regions, sub-Saharan Africa accounts for the highest mortality rates and the largest number of under-5 deaths. Under-5 mortality is mostly monitored at the national level, especially in low-income and middle-income countries, where estimates, such as from the Global Burden of Disease studies, rely on nationally representative surveys. However, little is known about the sub-national distribution of under-5 mortality across sub-Saharan Africa, leaving major gaps in the knowledge about at least three key issues. What is the distribution of under-5 mortality within sub-Saharan African countries? What portion of each country's children lives in regions with high mortality and slow progress? And to what extent has declining under-5 mortality been accompanied by a convergence in the mortality distribution? To address these questions, sub-national estimations of under-5 mortality will be needed, which have not so far been available for a large number of countries.

Added value of this study

Our data provide under-5 mortality estimates at a resolution of 0·1 × 0·1 degree (roughly 10 km × 10 km) for 28 sub-Saharan Africa countries from the 1980s to the 2000s. Despite the substantial overall declines in national mortality rates, only one-quarter of the variability in the levels and trends could be explained by national factors. We identified sub-national mortality hotspots in which mortality trends are not on target to reach the SDGs by 2030. Slightly more than half of these at-risk children resided in hotspots in Nigeria and DR Congo. We make the entirety of the gridded, interpolated data available for further analysis.

Implications of the available evidence

The sub-national variability of under-5 mortality in sub-Saharan Africa is substantial. Targeting of interventions for under-5 mortality reduction towards hotspot regions might be more important than national improvements for achieving the Sustainable Development Goals in sub-Saharan Africa. Although mortality is typically tracked and targeted at the national level, we show that local factors such as climate or geography seem to play a bigger part in explaining overall variability in under-5 mortality than do national factors. This finding calls into question prominent theories that argue that differences in national institutions are responsible for variation in health outcomes.

then be used to improve the targeting of interventions.[13–15] Nevertheless, the relative contribution of within-country and between-country differences in explaining under-5 mortality remains unknown. Improved understanding of the relative contribution of national and sub-national factors could provide insight into the drivers of mortality levels and declines in mortality, as well as improve the targeting of interventions to the areas where they are most needed.[16]

In this study, we aimed to provide novel perspectives on progress in under-5 mortality reductions by mapping and analysing sub-national levels and trends in under-5 mortality across sub-Saharan Africa. Using information from the Demographic and Health Surveys (DHS) on the location and timing of 3·24 million childbirths and 393 685 deaths across 28 African countries, we mapped variation in under-5 mortality at a fine spatial scale across three decades. We then used these data for four main analyses. First, by comparing within-country versus between-country variation in mortality over space and time, and by looking for abrupt differences in mortality at country borders, we aimed to quantify the extent to which variation in mortality is explained by country-level factors. Second, we attempted to identify the specific areas where progress in reducing under-5 mortality has lagged. This information can help in the targeting of interventions to so-called mortality hotspots (ie, those areas with both high mortality rates and slow declines). Third, we directly studied the extent to which national declines in under-5 mortality have been accompanied by increasing or decreasing inequality—ie, the extent to which the communities with the highest mortality had greater, equal, or lesser declines relative to communities with low mortality.[17,18] Finally, we combined our high-resolution estimates of under-5 mortality with data on other potential drivers to begin to identify underlying determinants of under-5 mortality.

For details about **Demographic and Health Surveys** see http://www.measuredhs.com

See Online for appendix

Methods

Data sources

The main data sources for this analysis were the DHS, nationally representative surveys that are conducted in many low-income and middle-income countries. DHS have a two-stage design, whereby a number of clusters are first selected from a list of enumeration areas created in a recent population census, and then households are randomly selected in each of the clusters, and women aged 15–49 years are selected for in-depth surveys.[19] In most survey waves, enumerators use global positioning system devices to collect geospatial information to identify the central point of each cluster's populated area. These coordinates are displaced by up to 2 km in urban clusters, 5 km in 99% of rural clusters, and 10 km in a random sample of 1% of rural clusters.[20] We used 82 surveys done in 28 sub-Saharan African countries between 1986 and 2013, which contained data on 31 037 clusters (information on the coverage of the study surveys is available in the appendix [pp 2–24]), including the location and timing of 3·24 million childbirths and 393 685 deaths.

Under-5 mortality rates

We used the complete birth histories of the women included in the DHS to estimate under-5 mortality rates. We calculated under-5 mortality in each cluster as 5m0, the number of under-5 deaths divided by the number of life-years of exposure among children under 5 years old. We estimated the under-5 mortality rate for each cluster in three decades: 1980s, 1990s, and 2000s. Births that occurred between Jan 1, 1980, and Dec 31, 1989, were included in the 1980s time period, regardless of the year when the survey data were collected. The 1990s and 2000s data periods were defined analogously. For each cluster, we counted the total number of under-5 deaths in the decade and the total number of under-5 years of exposure, using each survey's sample weights to adjust the death and exposure counts. We used 5m0 as our metric of choice because, compared with 1m0, the 5m0 is less susceptible to biases from age heaping. Furthermore, because the numerator and denominator are defined over the same period, 5m0 is less prone to censoring than are common alternative measures (eg 5q0), for which the denominator (number of births) is uncensored but the numerator (number of deaths before age 5) could be censored if the interview falls before a child's fifth birthday. Nevertheless, for comparability with the scientific literature, we also repeated the mapping portion of the analysis with the probability of death before age 5 years per 1000 livebirths, 5q0, finding similar results (appendix pp 9–24).

Geospatial interpolation

We interpolated cluster-specific under-5 mortality rates onto a 0·1 degree latitude×0·1 degree longitude grid (roughly 10 km×10 km at the equator) to estimate mortality levels for each cell of the grid. We used kernel density estimator interpolation approaches, which have previously been validated with DHS data (appendix pp 9–24).[21,22] We did not interpolate across country borders; we did interpolations separately for each of the 28 countries and for each decade. Within each country–decade, we interpolated deaths and child-years of exposure separately, and obtained mortality rates by dividing the interpolated number of deaths by the number of child-years of exposure inside each grid cell. We excluded from the analysis any cells in the grid with an estimated population of zero.[23]

To address concerns about the relative rarity of under-5 deaths,[24] we aggregated deaths to the cluster–decade level, observing that almost 70% of cluster–decades that we analysed included at least one under-5 death. To address potential concerns about non-representativeness at the local level, we used a bootstrap resampling procedure where clusters were sampled with replacement and mortality maps re-estimated (500 bootstraps). We then quantified the extent to which our results changed when clusters were dropped or duplicated, mimicking the effect of having drawn an alternate local sample (appendix pp 25–29).

Sources of variation in mortality

We quantified the importance of within-country versus between-country variation in each decade by least-squares regression of cell-level mortality estimates on a set of country indicator variables. The coefficient of determination in these regressions represents the proportion of total variation in under-5 mortality explained by between-country differences. We also used our interpolated mortality estimates to study whether under-5 mortality rates change discontinuously at country borders. Differences in outcomes across borders are often used as a way to understand the role of national institutions such as rule of law or property rights.[25] If these country-level factors were important in explaining variation in under-5 mortality, then we would expect mortality rates to demonstrably change across borders, since most neighbouring countries have different governance and institutional structures (appendix pp 30–42). Conversely, smooth mortality estimates across borders would support the role of local and environmental factors in explaining variation in mortality. For each of 40 borders, we estimate a sharp regression discontinuity at the border.[26] In essence, on each side of the border, we modelled mortality rates as a function of distance to the border. We then calculated the discontinuity at the border as the difference between the predicted mortality rates at the border given by the two functions on either side of the border (appendix pp 30–42).

Hotspot analysis

We use our data to identify under-5 mortality hotspots. We defined hotspots as areas in which, on the basis of annualised mortality reductions up to 2015, the projected mortality in 2030 is expected to remain higher than 25 deaths per 1000 child-years—a target set by the Sustainable Development Goals (SDGs). We then use a world population map to estimate the number of children younger than 5 years living in mortality hotspots in each country.[27]

Correlates of mortality

We studied the association between mortality and risk factors for which spatially fine data are available. We matched our gridded mortality estimates in the 2000s with georeferenced data on malaria burden (*Plasmodium falciparum* parasite rate) in 2005,[28] a count of civil conflict events in each location over the decade 2000–10,[29] and average ambient temperature measured over multiple decades in each location.[30] We used linear multivariate regression to investigate the association between these variables and under-5 mortality. Further details are available in the appendix (pp 43–52).

Role of the funding source

The funder of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report. The corresponding author had full access to

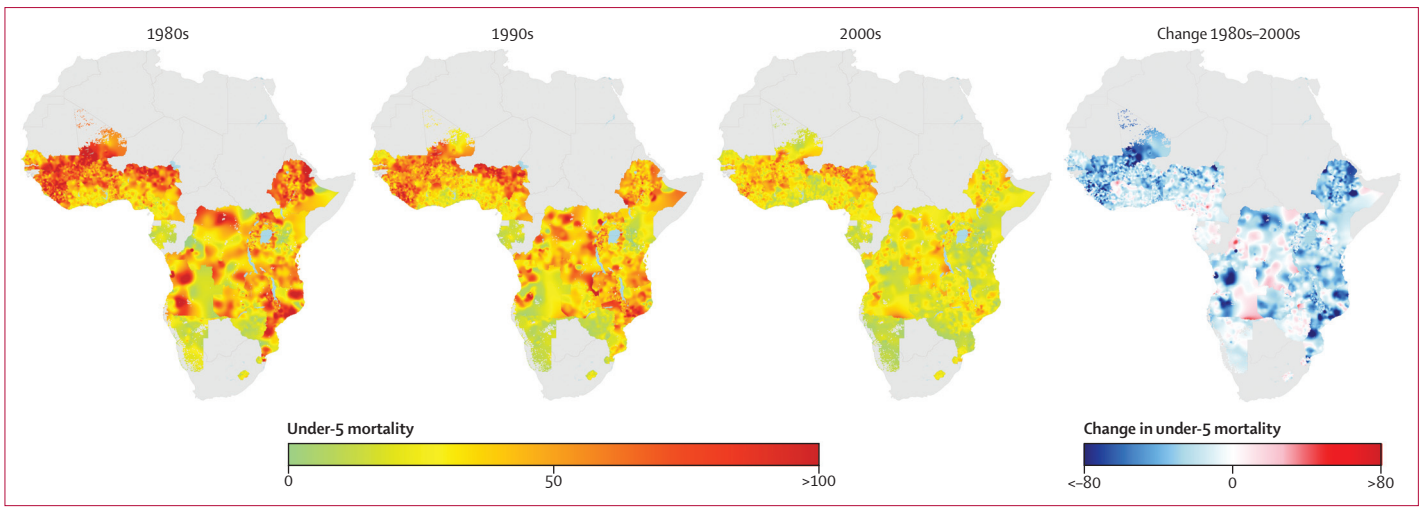


Figure 1: **Variation in under-5 mortality**
Maps show variation across sample countries in three decades, and the difference in cell-level mortality between the 1980s and 2000s. Mortality (and change in mortality) is represented as 5m0 (deaths per 1000 under-5 life-years).

	Overall cell-level variance explained by country dummies	Border pairs with significant cross-border changes in under-5 mortality (%)*
Mortality levels, 1980s	26·0%	10·0%
Mortality levels, 1990s	22·3%	15·0%
Mortality levels, 2000s	23·2%	7·5%
Changes in mortality, 1980s–2000s	24·5%	7·5%

Results for additional specifications are available in the appendix (p 33).
*Estimates reflect the results with our preferred specification, which applies a cubic polynomial functional form with three nodes and the Imbens-Kalyanaraman procedure for bandwidth selection; to account for the multiple comparisons problems that arise from simultaneously testing the significance of 40 border pairs, we used the Holm-Bonferroni p value correction method to control the familywise error rate.

Table: **Variation in under-5 mortality explained by between-country differences**

all the data in the study and had final responsibility for the decision to submit for publication.

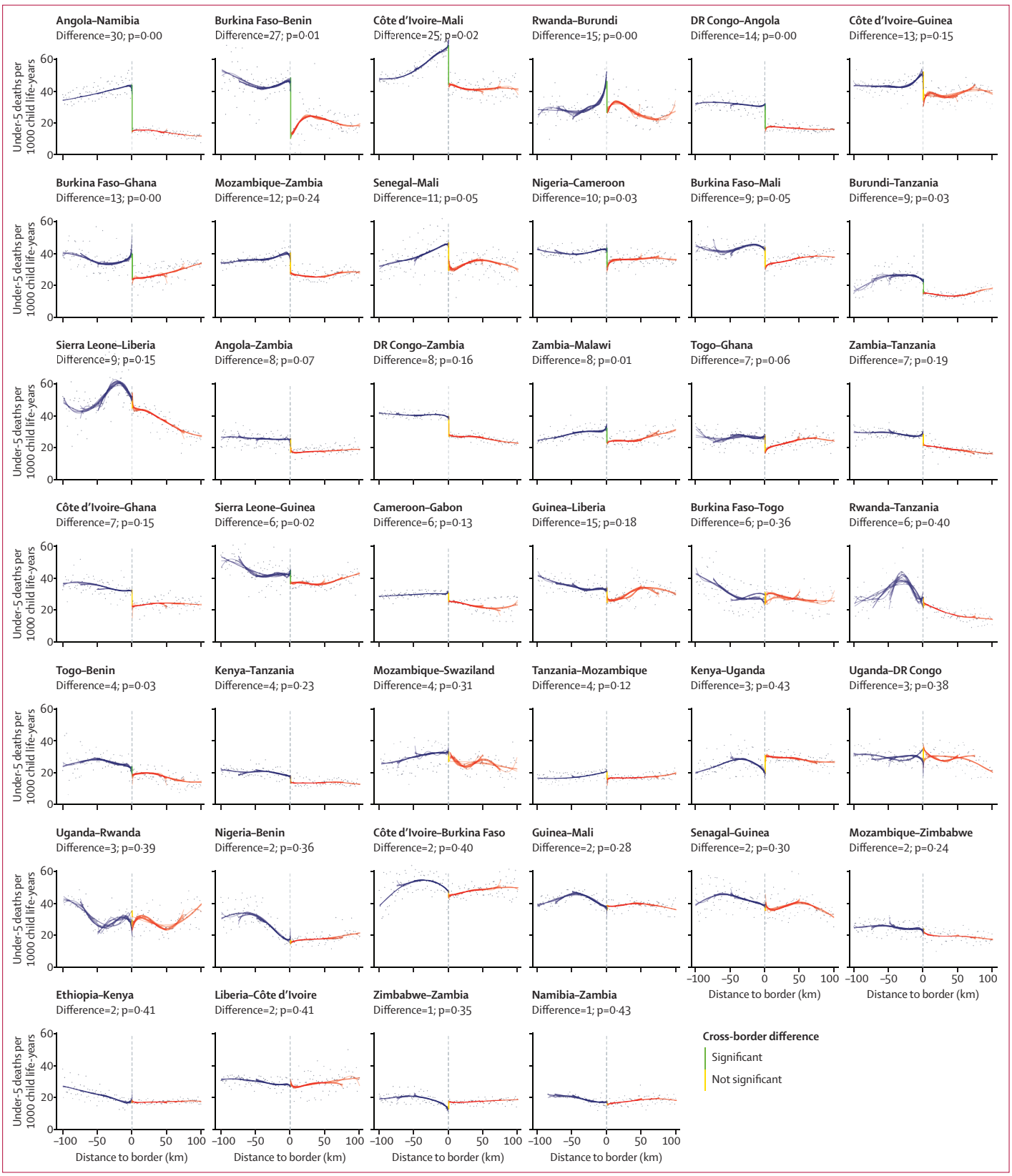
Results

Figure 1 shows the sub-national patterns of under-5 mortality for the 1980s, 1990s, and 2000s, and the changes in mortality between the 1980s and 2000s. We found substantial overall decline in under-5 mortality rates during this time period, but also noted two under-recognised sources of variation. First, large heterogeneity existed within countries, with mortality rates varying by at least a factor of 10 across locations within most countries, even in the 2000s. Second, the pace of reductions in under-5 mortality was also highly variable within countries and across the region as a whole. Although our estimates for specific grid cells were uncertain in some regions—especially in sparsely populated areas—the spatial patterns in the distribution of mortality within countries and over time were robust (appendix pp 23–29).

We quantified the importance of within-country versus between-country sources of variation (table). Between-country differences accounted for only 22·3–26·0% of the overall cross-sectional variation in mortality in the 1980s, 1990s, or 2000s. Similarly, between-country differences accounted for 24·5% of the variation in changes in mortality between the 1980s and 2000s. Roughly three-quarters of the variation in under-5 mortality in our data was attributable to factors that vary over space or time within countries. This finding did not seem to be an artifact of interpolation: the results were qualitatively unchanged when the analysis was restricted to pixels with lower uncertainty or to pixels in close proximity to DHS clusters (appendix p 45).

Figure 2 shows regression discontinuity estimates of differences in under-5 mortality for each of the 40 country-pairs during the 2000s. Ten (25%) of 40 borders showed differences in mortality of at least ten deaths per 1000 child-years, of which seven differences were significant significant at $p<0·05$. Of the remaining 30 border-pairs, only four were significantly different. Repeating this exercise for other decades, and after

Figure 2: **Border discontinuities in under-5 mortality rates for births that occurred from 2000–09**
Each panel represents a border pair. The vertical line in the centre of each panel shows the border, and the x-axis denotes distance from this border (increasing to the right and left). Dots show mortality rates in cells up to 100 km on either side of the border, red and blue lines show the model predictions used to fit these points, and the gap between the red and blue lines provides the point estimate of the difference in mortality at the border. Lines represent different models (3rd, 4th, 5th degree polynomials, cubic spline with 3,4,5 knots, local-linear regression) estimated with different bandwidths (0·5 degree, 1 degree, Imbens-Kalyanaraman optimal). Average regression discontinuity estimates across models for a given border are shown at the top of each panel, and vertical green lines at the border show significant differences ($p<0·05$).


Angola–Namibia
Difference=30; p=0·00
Burkina Faso–Benin
Difference=27; p=0·01
Côte d'Ivoire–Mali
Difference=25; p=0·02
Rwanda–Burundi
Difference=15; p=0·00
DR Congo–Angola
Difference=14; p=0·00
Côte d'Ivoire–Guinea
Difference=13; p=0·15
Burkina Faso–Ghana
Difference=13; p=0·00
Mozambique–Zambia
Difference=12; p=0·24
Senegal–Mali
Difference=11; p=0·05
Nigeria–Cameroon
Difference=10; p=0·03
Burkina Faso–Mali
Difference=9; p=0·05
Burundi–Tanzania
Difference=9; p=0·03
Sierra Leone–Liberia
Difference=9; p=0·15
Angola–Zambia
Difference=8; p=0·07
DR Congo–Zambia
Difference=8; p=0·16
Zambia–Malawi
Difference=8; p=0·01
Togo–Ghana
Difference=7; p=0·06
Zambia–Tanzania
Difference=7; p=0·19
Côte d'Ivoire–Ghana
Difference=7; p=0·15
Sierra Leone–Guinea
Difference=6; p=0·02
Cameroon–Gabon
Difference=6; p=0·13
Guinea–Liberia
Difference=15; p=0·18
Burkina Faso–Togo
Difference=6; p=0·36
Rwanda–Tanzania
Difference=6; p=0·40
Togo–Benin
Difference=4; p=0·03
Kenya–Tanzania
Difference=4; p=0·23
Mozambique–Swaziland
Difference=4; p=0·31
Tanzania–Mozambique
Difference=4; p=0·12
Kenya–Uganda
Difference=3; p=0·43
Uganda–DR Congo
Difference=3; p=0·38
Uganda–Rwanda
Difference=3; p=0·39
Nigeria–Benin
Difference=2; p=0·36
Côte d'Ivoire–Burkina Faso
Difference=2; p=0·40
Guinea–Mali
Difference=2; p=0·28
Senagal–Guinea
Difference=2; p=0·30
Mozambique–Zimbabwe
Difference=2; p=0·24
Ethiopia–Kenya
Difference=2; p=0·41
Liberia–Côte d'Ivoire
Difference=2; p=0·41
Zimbabwe–Zambia
Difference=1; p=0·35
Namibia–Zambia
Difference=1; p=0·43
Under-5 deaths per 1000 child life-years
0
20
40
60
−100 −50 0 50 100
Distance to border (km)
Cross-border difference
Significant
Not significant

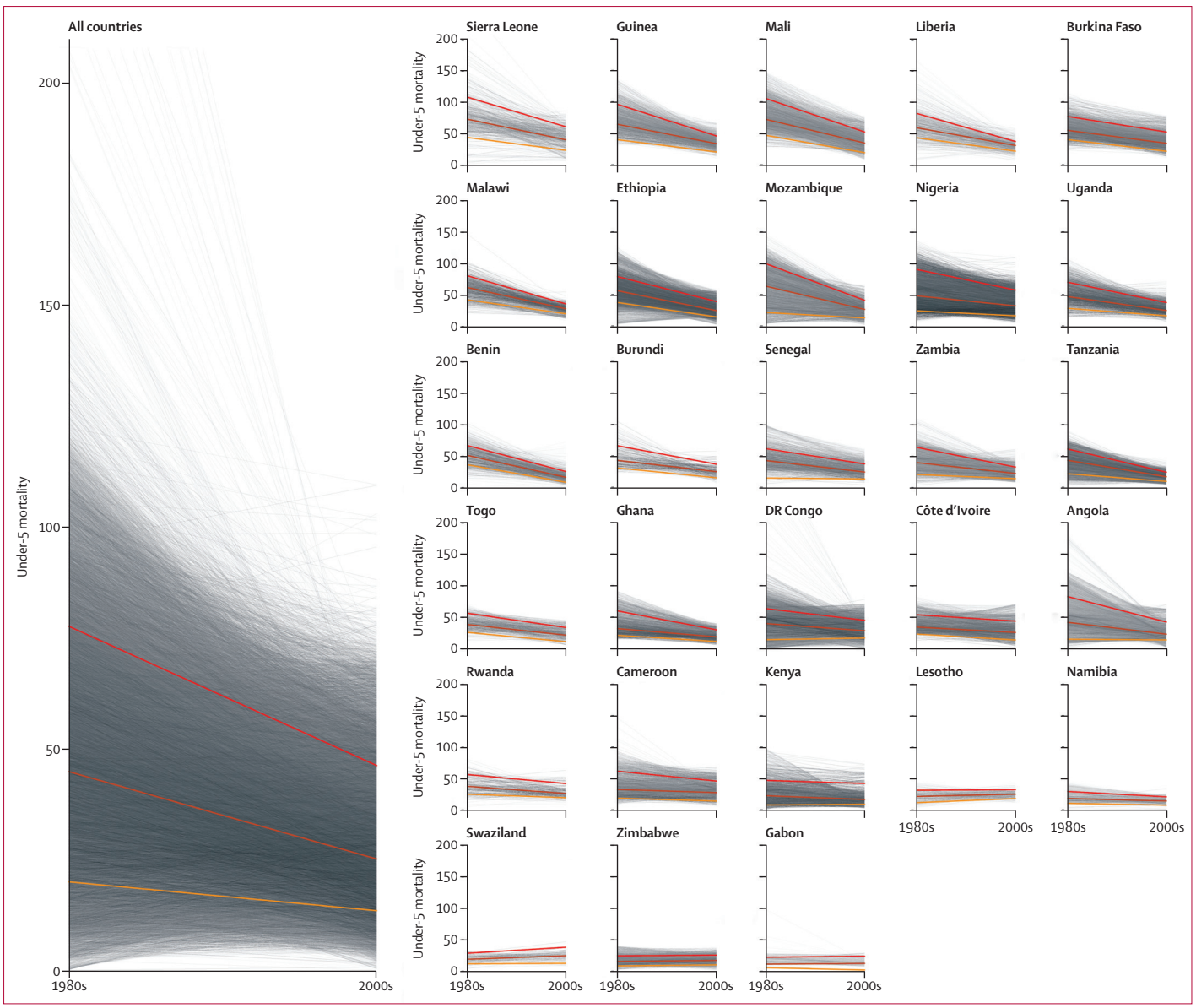


Figure 3: **Changes of distribution of mortality within countries and for the continent overall, 1980s to 2000s**
Under-5 mortality is the number of under-5 deaths per 1000 child life-years. Each grey line represents a grid cell from our maps; darker shaded lines have higher populations. Coloured lines show changes at the 10th (yellow line), 50th (orange line), and 90th percentiles (red line) of the mortality distribution in a given country.

controlling for multiple testing using a Holm-Bonferroni adjustment, only 7·5–15·0% of borders in our data were significantly different (table). These percentages were robust to alternative choices of how to estimate the discontinuity (appendix p 42), and were consistent with the previous analyses of within-country variability in mortality.

Given our results showing the limited role of country-level factors in explaining mortality patterns, we focused on characterisation of within-country variation. We examined whether aggregate progress at the continental or country level has come at the expense of widening inequality in mortality rates within countries—a common concern, but one that has received little empirical scrutiny. Figure 3 shows changes in cell-specific mortality rates between the 1980s and 2000s within each country and for the continent as a whole. The coloured lines show the 10th, 50th, and 90th percentiles of each country's mortality distribution over time, and the plot panels are arranged so that countries with the highest mortality rates in the 1980s appear first. Mortality levels have generally declined much faster at cells with higher mortality rates in the 1980s, and some localised areas with very high levels in the 1980s have declined at incredibly rapid rates. Although this

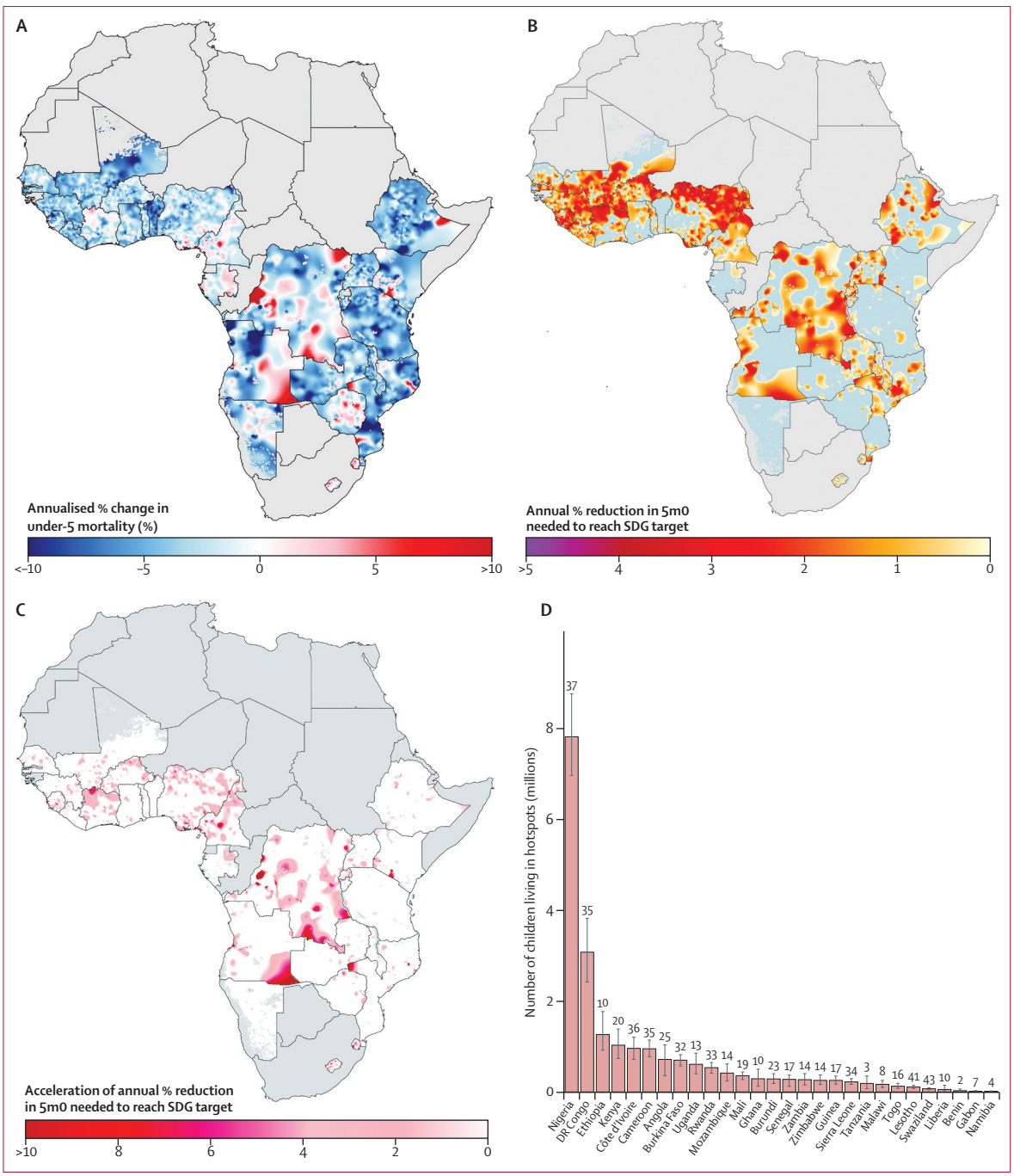


Figure 4: **Hotspots in under-5 mortality**
Hotspots in under-5 mortality. (A) Annualised percentage rate of change in under-5 mortality between 1980s and 2000s. (B) Annualised rates of decline needed between 2000s and 2030 to meet SDG target of under 25 deaths per 1000 child-years; blue indicates areas that have already reached target. (C) Mortality hotspots not currently on pace to meet the target; colours indicate percentage point acceleration in annual rate of change needed to meet target. (D) Number of children under 5 currently living in hotspots, by country; vertical lines indicates 95% CI for each country; numbers above bars represent the percentage of all children living in the country who reside in a hotspot. 5m0=number of under-5 deaths divided by the number of life-years of exposure among children under 5 years old. SDG=Sustainable Development Goals.

convergence has been particularly rapid in some countries (eg, Liberia, Malawi, Mozambique, and Tanzania), it has been slower elsewhere (eg, Côte d'Ivoire, Cameroon, and Kenya).

Details of our quantification of this convergence are available in the appendix (p 47). We found little systematic evidence of increasing inequality in under-5 mortality in the countries in our sample. In 26 of our 28 study

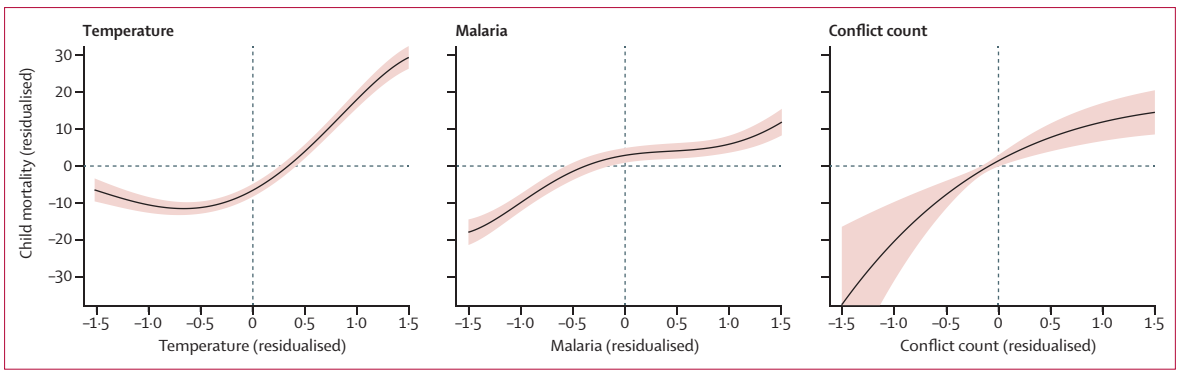


Figure 5: **Correlates of mortality at the level of grid cells**
Each panel shows the association between a given explanatory variable and mortality, controlling for the other two variables, as estimated with a 5th degree polynomial. Gridded mortality estimates in the 2000s were matched with georeferenced data on malaria burden (*Plasmodium falciparum* parasite rate) in 2005,[28] a count of civil conflict events in each location over the decade 2000–10,[29] and average ambient temperature measured over multiple decades in each location.[30] Axes are standardised to show percentage change in under-5 mortality per standard deviation change in the independent variable. 95% CIs are shown in pink.

countries, the decline in under-5 mortality at the 90th percentile of the distribution (the high-mortality end of the distribution) was faster than at the 10th percentile. Expressed as the percentage change in the mortality level from the 1980s to the 2000s, 18 out of 28 countries had faster declines at the 90th percentile than at the 10th percentile of the distribution. By both of these measures, mortality rates within countries have on average converged since the 1980s.

Nevertheless, convergence has not been universal, and our data show areas in which under-5 mortality rates are on a trajectory to remain high if progress is not accelerated. Figure 4A shows annualised rates of change in under-5 mortality between the 1980s and 2000s. We calculated the annualised rates of change in mortality needed to achieve a mortality rate below the SDG target on the basis of our estimates of under-5 mortality in the 2000s (figure 4B). Figure 4C shows the difference between the historical rate and the rate of change needed in the future to meet the 2030 target. For example, a value of 4 shows an area where annual rates of change up to 2030 need to be four percentage points higher than observed historical rates if the target is to be met. We deemed any areas not coloured white in the map to be hotspots—areas not on pace to meet the target, and where additional intervention or support might be needed. We emphasise that our estimates only pertain to countries with DHS data available; mortality hotspots might exist in other countries such as Sudan or Somalia, but suitable data were not available to examine this possibility.

We found substantial variation between countries in the proportion of the under-5 population living in hotspot areas (figure 4D). In only three countries do less than 5% of children live in hotspots: Benin, Namibia, and Tanzania. Conversely, countries with a large (>30%) share of eligible children living in hotspots include those with relatively small increases in under-5 mortality over time (eg, Swaziland and Lesotho), as well as countries with high mortality and less regional progress over time (Nigeria and DR Congo). Overall, we calculated that 23% (95% CI 18–29) of the children in the 28 countries analysed lived in hotspot locations, most of whom (52%, 95% CI 47–58) lived in Nigeria and DR Congo.

Finally, we related local mortality rates to georeferenced data on hypothesised local drivers. Our primary goal in this analysis was to show that existing spatial datasets can be effectively used in understanding local variation in mortality in sub-Saharan Africa, rather than to make any causal claims about local drivers of mortality variation. We found that mortality rates are positively correlated with temperature, malaria, and recent conflict (figure 5). Per standard deviation increase in each of these independent variables, mortality rates increase by 1·3% for conflict, 10·9% for malaria, and 16·4% for temperature (appendix p 49). We again emphasise that these are cross-sectional associations and, in the absence of more careful work addressing potential confounds, should not be interpreted causally.

Discussion

Our results show that under-5 mortality levels and trends in sub-Saharan Africa nations are highly heterogeneous, with sub-national factors accounting for more than three-quarters of the overall variation in mortality. Our findings raise important questions about prevailing approaches to the monitoring of mortality and targeting of interventions. At a national scale, our findings agree with other estimates of the distribution and trends in under-5 mortality; on average, under-5 mortality has declined substantially between the 1980s and 2000s, yet high mortality levels remain in parts of central and western Africa.[31,32] However, our results show substantial spatial variation in the patterns underlying national reductions in under-5 mortality. Across any of the three decades, mortality levels within countries such as Nigeria, Kenya, and Côte d'Ivoire ranged from among the lowest to among the highest in the continent. Additionally, each of these countries has

had substantial declines in under-5 mortality in some regions, but stagnation or even increases in others. Areas with stagnating or increasing under-5 mortality existed within nearly all countries in this study, including those with substantial national declines in under-5 mortality. Our data suggest that focusing on national under-5 mortality as the main metric for monitoring progress is likely to be inadequate for understanding where and why children are still dying.

Recording and analysing of geographical variation in health outcomes in developed countries has been an influential approach for understanding the source of health inequities, and continues to yield insights of broad policy and academic interest.[10–12] Whereas other studies have quantified sub-national variability in health outcomes in individual developing countries, this study is the first, to our knowledge, to record and analyse local-level mortality variation across a large number of less-developed countries—an analysis that enables quantification of the relative importance of national and sub-national variation in explaining overall mortality.[33,34]

Our finding of substantial spatial variation in mortality is further strengthened by our analysis of borders. If national governments possessed differential abilities to effectively implement health programmes, for example because of differences in resources or governance capacity, then these countries would be expected to follow distinct trajectories that might manifest as differences of health status at country borders. The fact that we found mainly smooth mortality patterns across most borders, and little systematic evidence of border discontinuities again shows the importance of local drivers of mortality that do no respect borders: eg, environmental factors such as climate conditions suitable for Anopheles mosquitoes or soil conditions that affect food availability.

In finding that a only a small proportion of the variation in under-5 mortality is explained by national factors, our analysis suggests that there could be unrealised benefits from the monitoring and targeting of progress at a finer spatial scale than has previously been used. Although national institutions have agency to follow through on agreements such as the SDGs, the high variability that we identified suggests that local conditions might have a greater role in driving future trends in mortality. Policies and interventions that target areas with exceptionally high mortality might be more effective than national policies for addressing hotspots that are otherwise not on pace to reach SDG targets. Finally, our data show that, although most countries showed convergence in the distribution of mortality between the 90th and 10th percentiles, this trend was not universal. Understanding the sources of non-convergent development could help make future mortality declines more equitable.

The limitations of our approach deserve further consideration. In addition to the recall bias inherent in asking women about births and deaths as long as 20 years before the date of the interview, location bias might also affect the precision of our measurements if the area where the woman is interviewed was distant from the area where her children were raised or died (appendix pp 12, 13).[24] Our main interpolation method does not assume that mortality in nearby clusters is spatially correlated. In a robustness check, we used ordinary kriging (Gaussian process regression), which is often used in geoadditive models, to account for potential spatial correlation when estimating cell-level mortality.[33,35,36] We found similar estimates using kriging as compared with kernel density (appendix pp 11, 12). Our estimates are most certain in areas with high density of DHS clusters, and least certain in remote areas without nearby DHS clusters (appendix p 48). However, this uncertainty did not affect the primary findings on sources of variation and hotspots. The complex sampling design of DHS surveys and the hierarchical nature of the data mean that sampling variation and clustering could affect our findings. Finally, the correlations that we noted between mortality, temperatures, malaria, and conflict are consistent with other studies, but should be interpreted as cross-sectional associations that require further study.

Our work enables further study of the determinants of under-5 mortality declines. Currently, understanding of these determinants is hampered by long-standing and steady declines in mortality at the country level, and the challenges these steady declines pose for identification of attributable causes of mortality declines or increases. The creation of a high-resolution mortality database with high levels of variation across space and time provides new opportunities for a deeper understanding of the role that environmental, economic, or political conditions play in shaping mortality outcomes. For example, further examination of the role of environmental factors such as climate and mosquito suitability conditions could help to inform long-standing questions about the relative contributions of geography and institutions in shaping comparative development.[25,37]

Contributors

MB contributed to the study design, analysis, interpretation, writing of the report, and revisions. SHN contributed to the study design, the main statistical analyses, interpretation, production of figures and tables, and revisions to the report. EB contributed to the study design, data preparation, interpretation, writing of the report, and revisions.

Declaration of interests

We declare no competing interests.

Acknowledgments

This work was funded by The Stanford Woods Institute for the Environment. EB is funded by the Doris Duke Charitable Foundation.

References

1 Wang H, Liddell CA, Coates MM, et al. Global, regional, and national levels of neonatal, infant, and under-5 mortality during 1990–2013: a systematic analysis for the Global Burden of Disease Study 2013. *Lancet* 2014; **384:** 957–79.

2 United Nations Department for Economic and Social Affairs. World population prospects, the 2015 Revision. 2015. http://esa.un.org/unpd/wpp/ (accessed June 10, 2016).

3 You D, Hug L, Ejdemyr S, et al. Global, regional, and national levels and trends in under-5 mortality between 1990 and 2015, with scenario-based projections to 2030: a systematic analysis by the UN Inter-agency Group for Child Mortality Estimation. *Lancet* 2015; **386:** 2275–86.

4 Lozano R, Wang H, Foreman KJ, et al. Progress towards Millennium Development Goals 4 and 5 on maternal and child mortality: an updated systematic analysis. *Lancet* 2011; **378:** 1139–65.

5 Gaffey MF, Das JK, Bhutta ZA. Millennium Development Goals 4 and 5: Past and future progress. *Semin Fetal Neonatal Med* 2015; **20:** 285–92.

6 United Nations. The Millennium Development Goals Report 2015. 2015. http://www.un.org/millenniumgoals/2015_MDG_Report/pdf/MDG%202015%20rev%20(July%201).pdf (accessed May 25, 2016).

7 Gakidou E, Cowling K, Lozano R, Murray CJ. Increased educational attainment and its effect on child mortality in 175 countries between 1970 and 2009: a systematic analysis. *Lancet* 2010; **376:** 959–74.

8 Muldoon KA, Galway LP, Nakajima M, et al. Health system determinants of infant, child and maternal mortality: a cross-sectional study of UN member countries. *Global Health* 2011; **7:** 42.

9 Moreno-Serra R, Smith PC. Does progress towards universal health coverage improve population health? *Lancet* 2012; **380:** 917–23.

10 Chetty R, Stepner M, Abraham S, et al. The association between income and life expectancy in the United States, 2001–2014. *JAMA* 2016; **315:** 1750–66.

11 Fisher ES, Wennberg DE, Stukel TA, Gottlieb DJ, Lucas FL, Pinder EL. The implications of regional variations in Medicare spending. Part 2: health outcomes and satisfaction with care. *Ann Intern Med* 2003; **138:** 288–98.

12 Birkmeyer JD, Reames BN, McCulloch P, Carr AJ, Campbell WB, Wennberg JE. Understanding of regional variation in the use of surgery. *Lancet* 2013; **382:** 1121–29.

13 Lai Y-S, Biedermann P, Ekpo UF, et al. Spatial distribution of schistosomiasis and treatment needs in sub-Saharan Africa: a systematic review and geostatistical analysis. *Lancet Infect Dis* 2015; **15:** 927–40.

14 Hay SI, Guerra CA, Gething PW, et al. A world malaria map: *Plasmodium falciparum* endemicity in 2007. *PLoS Med* 2009; **6:** 286.

15 Anderson S-J, Cherutich P, Kilonzo N, et al. Maximising the effect of combination HIV prevention through prioritisation of the people and places in greatest need: a modelling study. *Lancet* 2014; **384:** 249–56.

16 Bryce J, Victora CG, Black RE. The unfinished agenda in child survival. *Lancet* 2013; **382:** 1049–59.

17 Waage J, Banerji R, Campbell O, et al. The Millennium Development Goals: a cross-sectoral analysis and principles for goal setting after 2015: Lancet and London International Development Centre Commission. *Lancet* 2010; **376:** 991–1023.

18 Carrera C, Azrack A, Begkoyian G, et al. The comparative cost-effectiveness of an equity-focused approach to child survival, health, and nutrition: a modelling approach. *Lancet* 2012; **380:** 1341–51.

19 Aliaga A, Ren R. Optimal sample sizes for two-stage cluster sampling in demographic and health surveys: working paper 30. Calverton, MD: ORC Macro, 2006.

20 Burgert CR, Colston J, Roy T, Zachary B. Geographic displacement procedure and georeferenced data release policy for the Demographic and Health Surveys. DHS Spatial Analysis Reports 7. Calverton, MD: United States Agency for International Development, 2013.

21 Larmarange J, Vallo R, Yaro S, Msellati P, Méda N. Methods for mapping regional trends of HIV prevalence from Demographic and Health Surveys (DHS). *CyberGeo* 2011; published online Oct 26. DOI:10.4000/cybergeo.24606.

22 Larmarange J, Bendaud V. HIV estimates at second subnational level from national population-based surveys. *AIDS* 2014; **28:** S469–76.

23 Rose AN, Bright EA. The LandScan Global Population Distribution Project: current state of the art and prospective innovation. Oak Ridge, TN: Oak Ridge National Laboratory (ORNL), 2014.

24 Burgert CR. Spatial interpolation with Demographic and Health Survey data: key considerations. DHS Spatial Analysis Reports 9. Calverton, MD: United States Agency for International Development, 2013.

25 Acemoglu D, Robinson JA. Why nations fail: the origins of power, prosperity and poverty. New York, NY: Crown Publishers, 2012.

26 Imbens GW, Lemieux T. Regression discontinuity designs: a guide to practice. *J Econom* 2008; **142:** 615–35.

27 Linard C, Gilbert M, Snow RW, Noor AM, Tatem AJ. Population distribution, settlement patterns and accessibility across Africa in 2010. *PLoS One* 2012; **7:** e31743.

28 Bhatt S, Weiss D, Cameron E, et al. The effect of malaria control on *Plasmodium falciparum* in Africa between 2000 and 2015. *Nature* 2015; **526:** 207–11.

29 Melander E, Sundberg R. Climate change, environmental stress, and violent conflict: tests introducing the UCDP Georeferenced Event Dataset. International Studies Association Annual Conference "Global Governance: Political Authority in Transition"; Montreal, QC, Canada; March 16, 2011.

30 Hijmans RJ, Cameron SE, Parra JL, Jones PG, Jarvis A. Very high resolution interpolated climate surfaces for global land areas. *Int J Climatol* 2005; **25:** 1965–78.

31 Naghavi M, Wang H, Lozano R, et al. Global, regional, and national age-sex specific all-cause and cause-specific mortality for 240 causes of death, 1990–2013: a systematic analysis for the Global Burden of Disease Study 2013. *Lancet* 2015; **385:** 117–71.

32 UN Inter-agency Group for Child Mortality Estimation. Child mortality estimates. http://www.childmortality.org/ (accessed May 14, 2016).

33 Adebayo SB, Fahrmeir L. Analysing child mortality in Nigeria with geoadditive discrete-time survival models. *Stat Med* 2005; **24:** 709–28.

34 Kandala N-B, Mandungu TP, Mbela K, et al. Child mortality in the Democratic Republic of Congo: cross-sectional evidence of the effect of geographic location and prolonged conflict from a national household survey. *BMC Public Health* 2014; **14:** 1.

35 Kazembe L, Clarke A, Kandala N-B. Childhood mortality in sub-Saharan Africa: cross-sectional insight into small-scale geographical inequalities from Census data. *BMJ Open* 2012; **2:** e001421.

36 Kandala N-B, Ghilagaber G. A geo-additive Bayesian discrete-time survival model and its application to spatial analysis of childhood mortality in Malawi. *Qual Quant* 2006; **40:** 935–57.

37 Sachs JD. Government, geography, and growth. The True Drivers of Economic Development. *Foreign Affairs*, 2012. https://www.foreignaffairs.com/reviews/review-essay/government-geography-and-growth (accessed May 15, 2016).