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 Development 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.

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.1,2 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.3–5

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
then be used to improve the targeting of interventions.11–15 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.

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 31037 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 393685 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 $5m_0$, 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 $5m_0$ as our metric of choice because, compared with $1m_0$, the $5m_0$ is less susceptible to biases from age heaping. Furthermore, because the numerator and denominator are defined over the same period, $5m_0$ is less prone to censoring than are common alternative measures (eg $5q_0$), 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, $5q_0$, 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). 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. To address concerns about the relative rarity of under-5 deaths, 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. If these country-level factors were important in explaining variation in under-5 mortality, then we would expect mortality rates to discontinuously 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. 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.

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, a count of civil conflict events in each location over the decade 2000–10, and average ambient temperature measured over multiple decades in each location. 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

www.thelancet.com/lancetgh Vol 4 December 2016 e938
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).

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

<table>
<thead>
<tr>
<th></th>
<th>Overall cell-level variance explained by country dummies</th>
<th>Border pairs with significant cross-border changes in under-5 mortality (%)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mortality levels, 1980s</td>
<td>26.0%</td>
<td>10.0%</td>
</tr>
<tr>
<td>Mortality levels, 1990s</td>
<td>22.3%</td>
<td>15.0%</td>
</tr>
<tr>
<td>Mortality levels, 2000s</td>
<td>23.2%</td>
<td>7.5%</td>
</tr>
<tr>
<td>Changes in mortality, 1980s–2000s</td>
<td>24.5%</td>
<td>7.5%</td>
</tr>
</tbody>
</table>

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.

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
Under-5 deaths per 1000 child life-years

- 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=0.11
- 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=6; p=0.18
- Burkina Faso–Togo: Difference=6; p=0.36
- Rwanda–Tanzania: Difference=6; p=0.40
- Togo–Benin: Difference=5; p=0.03
- Kenya–Tanzania: Difference=4; p=0.23
- Mozambique–Swaziland: Difference=4; p=0.31
- Tanzania–Mozambique: Difference=4; p=0.32
- Kenya–Uganda: Difference=4; 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=0.60
- Guinea–Mali: Difference=2; p=0.28
- Senegal–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

Cross-border difference
- Significant
- Not significant
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 (yellow line), 50th (orange line), and 90th percentiles (red line) of the mortality distribution in a given country.
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...
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.39–42 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).44 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.35,37

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


