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Neonatal and perinatal mortality in the urban continuum: a geospatial analysis of the household survey, satellite imagery and travel time data in Tanzania

Peter M Macharia ,[1,2] Lenka Beňová ,[3] Jessie Pinchoff ,[4] Aline Semaan,[3] Andrea B Pembe,[5] Aliki Christou ,[3] Claudia Hanson [6,7]

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PMM and LB are joint first authors.

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For numbered affiliations see end of article.

Correspondence to
Dr Peter M Macharia; pmacharia@kemri-wellcome.org

ABSTRACT

Introduction Recent studies suggest that the urban advantage of lower neonatal mortality in urban compared with rural areas may be reversing, but methodological challenges include misclassification of neonatal deaths and stillbirths, and oversimplification of the variation in urban environments. We address these challenges and assess the association between urban residence and neonatal/perinatal mortality in Tanzania.

Methods The Tanzania Demographic and Health Survey (DHS) 2015–2016 was used to assess birth outcomes for 8915 pregnancies among 6156 women of reproductive age, by urban or rural categorisation in the DHS and based on satellite imagery. The coordinates of 527 DHS clusters were spatially overlaid with the 2015 Global Human Settlement Layer, showing the degree of urbanisation based on built environment and population density. A three-category urbanicity measure (core urban, semi-urban and rural) was defined and compared with the binary DHS measure. Travel time to the nearest hospital was modelled using least-cost path algorithm for each cluster. Bivariate and multilevel multivariable logistic regression models were constructed to explore associations between urbanicity and neonatal/perinatal deaths.

Results Both neonatal and perinatal mortality rates were highest in core urban and lowest in rural clusters. Bivariate models showed higher odds of neonatal death (OR=1.85; 95% CI 1.12 to 3.08) and perinatal death (OR=1.60; 95% CI 1.12 to 2.30) in core urban compared with rural clusters. In multivariable models, these associations had the same direction and size, but were no longer statistically significant. Travel time to the nearest hospital was not associated with neonatal or perinatal mortality.

Conclusion Addressing high rates of neonatal and perinatal mortality in densely populated urban areas is critical for Tanzania to meet national and global reduction targets. Urban populations are diverse, and certain neighbourhoods or subgroups may be disproportionately affected by poor birth outcomes. Research must capture, understand and minimise risks specific to urban settings.

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ The urban advantage, suggesting better health outcomes in urban compared with rural populations, has been questioned, both for adult and child mortality.
⇒ An analysis using Demographic and Health Survey data in Tanzania in 2015–2016 showed a twofold higher risk of neonatal mortality in urban compared with rural areas.
⇒ A reversal of the urban advantage in neonatal survival might be occurring in other sub-Saharan African countries.

WHAT THIS STUDY ADDS

⇒ Our work suggests that the categorisation of locations as urban or rural on the 2015–2016 Demographic and Health Survey in Tanzania may be both simplistic and inaccurate.
⇒ Risks of neonatal and perinatal mortality are highest in core, densely populated urban areas in mainland Tanzania, and lowest in rural areas.
⇒ Travel time to nearest public hospital was not associated with neonatal or perinatal mortality in mainland Tanzania.

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE OR POLICY

⇒ Urbanicity as an exposure variable follows a spectrum which needs to be better measured and understood.
⇒ More research is urgently needed to understand the neonatal and perinatal mortality in core urban areas to guide specific actions.
⇒ Known risk factors such as anaemia and young maternal age continue to play a role in neonatal and perinatal mortality and must be urgently addressed.

INTRODUCTION

Africa is the most rapidly urbanising continent, with its population expected to double by 2050 and two-thirds of this growth will be in urban areas.[1] Health status and outcomes have generally been described as better in urban compared with rural areas, likely due to a variety of factors, including better infrastructure and improved access to healthcare.[2] However, this phenomenon is not universal and shows signs of reversal.[3 4] A recent study of Demographic and Health Surveys (DHS) data collected between 1992 and 2018 in 53 low-income and middle-income countries found that the urban advantage in adult mortality has diminished while an urban advantage continues to be observed among children under-5 years of age.[5]

In sub-Saharan Africa (SSA), neonatal mortality has historically been higher in rural areas compared with urban ones[6] and is posited to be related to a combination of socioeconomic factors (maternal education, nutrition, care affordability) and care accessibility (more births occurring in health facilities, shorter distance and travel time to health facilities). With rapid reductions in under-5 mortality, the proportions of under-5 deaths have concentrated in infancy, specifically during the neonatal period.[7] Recent population surveys have shown that in SSA, the urban advantage in neonatal mortality rate (NMR) might be waning. The most extreme example is Tanzania where urban neonatal mortality (40/1000 live births) is twice the level in rural areas (20/1000 live births) and this difference persists even when some confounders are adjusted for (2015–2016 DHS). Within the neonatal period, the disparity between urban and rural areas is highest among deaths on days 1–7 after birth.[6] The potential drivers of this observed higher urban neonatal mortality are not well understood; several hypotheses have been proposed and multiple factors could be at play such as limited access to clean water and sanitation, variable quality of maternal and newborn healthcare and poor air quality, all highly prevalent in urban settings in general and informal settlements in particular.[6] Further, extreme inequality is present within urban areas, despite improved resources and infrastructure.[8]

There is no agreement on a definition of the exposure of urbanicity, but satellite derived data sets offer an opportunity to use more objective and continuous measures which quantify the degree of urbanisation at high spatial resolution as a combination of built environment and population density. This is derived independently from national administrative boundaries or designations. Previous studies found that satellite derived urbanicity measures strongly align with administrative data but may fail to capture some rural areas.[9] By using satellite derived data, multiple categories of 'urban' can be derived to validate the observed pattern of higher neonatal mortality in urban areas. It would also allow for an exploration of potential misclassification bias when using DHS-based classification, that is, usually based on country administrative regions or population thresholds to define urban or rural in some countries compared with satellite derived classification based on high resolution population density, built-up areas and other land use and cover classes. A second issue for research to understand in the association between neonatal mortality and urbanicity is the potential misclassification between stillbirths and neonatal deaths due to challenges with establishing whether there were signs of life after birth.[10] The combination of omission of stillbirths, potential misclassification of birth outcomes (neonatal deaths and stillbirths), misclassification or oversimplification of urbanicity and residual confounding may mask the true direction and strength of the association between urbanicity and neonatal mortality.

With a view to address these limitations affecting our previous work,[6] we aim to more accurately estimate the direction and strength of the association between urban residence and neonatal mortality in mainland Tanzania. We address the limitations by reducing misclassification of exposure by using geospatial techniques to reclassify urban/rural areas and use a more granular measure of urbanicity (three categories), and by reducing misclassification of outcome (neonatal deaths reported as stillbirth) by also examining perinatal mortality (stillbirths and early neonatal deaths combined).

METHODS

Overview

We start by identifying recent births occurring to women of reproductive age sampled on the Tanzania DHS in 2015–2016. Based on the coordinates of the household clusters where women live, we created an alternative urbanicity using satellite imagery in lieu of the binary residence variable provided by the DHS. Confounders were retrieved from the DHS or generated through geospatial modelling. We then used bivariate and multilevel multivariable logistic regression models to assess the strength of the association between urban residence and (1) neonatal mortality and (2) perinatal mortality.

Data sources and measures

We used the most recent DHS conducted in Tanzania in 2015–2016. DHS are cross-sectional nationally representative household surveys which use standard model questionnaires which countries can adapt. DHS respondents are women of reproductive age (15–49 years), and in several countries men are also interviewed. The surveys include questions on household and individual characteristics, fertility, maternal and child health, mortality, among others. The survey sampling design was based on a two-stage strategy, the first stage involved selection of sampling points (clusters, based on the 2012 Tanzanian census enumeration areas (EAs)) and the second selection of households within clusters. The stratification allowed estimation of certain indicators for 25 regions in mainland Tanzania. Each EA typically contains 20–30 households randomly selected to be surveyed from about 100–300 households per cluster. To reduce the disclosure risk, the cluster is first assigned the coordinates of the EA centre and then geomasked by displacing the Global Positioning System coordinates. Urban clusters were displaced by up to 2 km while rural clusters were displaced by up to 5 km, with a further 1% randomly selected rural clusters displaced by up to 10 km.[11]

Population

Our study population included women aged 15–49 years at the time of the DHS who lived in sampled households and agreed to participate in the survey. We analysed all live births and stillbirths occurring in the 5 years prior to the survey reported by participating women who had a permanent address in mainland Tanzania.

Outcome variables

The main outcome of this study was neonatal death. While neonatal deaths are usually defined as deaths between birth and day 28, we also included deaths reported on day 29. This is due to the coding of the response in the DHS data set and to remain consistent with the cut-off that the DHS report used.[12] We defined NMR as the number of neonatal deaths per 1000 live births. We further assessed early (within the first 7 days of life, within which we separated deaths on day of birth) and late (8–29 days inclusive) NMR. The secondary outcome was perinatal death, defined as a combination of stillbirths (defined as deaths of babies at or after 7 months of pregnancy and before birth in line with the WHO recommended definition of late gestation stillbirth for international comparisons) and early neonatal deaths. Perinatal mortality rate was expressed as the number of stillbirths and early neonatal deaths per 1000 pregnancies of gestational age 7 or more months, including live births. We extracted stillbirths from the DHS contraceptive calendar based on DHS guidance.[13,14]

Main exposure

Our primary explanatory variable of interest was *residence* (urban or rural) based on DHS designation and *urbanicity* (core urban, semi-urban and rural) derived from satellite imagery. As an alternative to the DHS urban and rural classifications, we derived three classes of the urban continuum (urbanicity)—rural, semi-urban and core urban based on satellite imagery. We used the 2015 Global Human Settlement Layer-settlement model (GHS-SMOD)[15,16] to classify the location of DHS clusters into different degrees of urbanicity, namely core urban, semi-urban and areas in transition and rural areas. Details on how these classes were generated are provided in online supplemental file 1.

Modelling travel time to hospitals

Given that short distances in urban areas can obscure long travel times,[17] we also included a consideration for accessibility of emergency obstetrical healthcare during pregnancy and childbirth generally provided only in hospitals as a potential explanation (effect moderator) between urbanicity and neonatal mortality. A proxy of geographical accessibility to hospital was not available in the DHS and was thus modelled independently for each cluster. It was proxied by the time taken to travel between a DHS cluster and the nearest public hospital, based on a least-cost path algorithm implemented in a Geographical Information System via WHO AccessMod 5 software (alpha V.5.7.8)[18] widely used across healthcare applications in SSA.[19] The detailed steps undertaken to compute travel time are provided in online supplemental file 1.

Confounder variables

Potential confounders related to both neonatal/perinatal mortality and urbanicity were identified based on the literature. We relied on confounders available in the DHS capturing the lived environment of the woman (geographical zone), household characteristics, socioeconomic characteristics of the woman and variables capturing information about the pregnancy and health-seeking behaviour during index pregnancy and childbirth. Some of the variables were only available for live births and others still only for the *most recent* live birth in the 5-year period (online supplemental file 2).

Data analysis

We conducted the analysis in three steps. First, we explored the correspondence between the DHS characterisation of clusters as urban or rural in comparison to the three categories based on GHS-SMOD. We also describe the distribution of mean travel time to the nearest public hospital among the study population for both the DHS and GHS-SMOD urban–rural classifications. Second, we described characteristics of the sample and calculated neonatal and perinatal mortality rates, and the distribution of age at death using both DHS and GHS-MOD categorisations. Third, we tested bivariate and multivariable associations between the GHS-MOD urbanicity measure and neonatal/perinatal mortality. The main hypothesis was that there is an association between urbanicity and neonatal/perinatal mortality. Due to inconsistent availability of key variables, we ran four separate multivariable models. The first three models had neonatal mortality as an outcome and were conducted: (1) among all live births, (2) among the most recent live births and (3) among most recent live births with newborn's birth weight and antenatal care (ANC) history available. The fourth model included all births, and the outcome was perinatal mortality.

To assess the effect of urbanicity on neonatal/perinatal mortality, our model building strategy aimed to adjust for confounding, not to overparameterise and to account for any multilevel effects. The selection of variables into adjusted regression models followed previously used approaches.[20–22] First, based on previous research, we identified all potential confounders (variables that influence both mortality and residence). For each confounder, we ran a bivariate regression to estimate the crude association between each potential confounder and both outcomes (neonatal and perinatal mortality). Only confounders significant at p value<0.20 were incorporated into the subsequent multivariable regression analysis step.

In the multivariable multilevel logistic regression model, we added urbanicity as the first variable, followed by one confounder at a time, starting with the confounder with the lowest p value in the bivariate model. Confounders were only retained in the model if they met two criteria; (1) having a p value<0.05, and (2) effects on the adjusted OR of the confounders already selected (ie, confounders causing at least a 10% change in the effect size of variables were retained even if not significant at p<0.05). Confounders not meeting these criteria were not retained in the final models except for the geographical zone, which was included a priori to capture the lived environment.

Further, we accounted for the multistage sampling design and nesting structure in the DHS data through multilevel hierarchical modelling regardless of the significance.[23 24] This strategy accounts for contextual factors which are not captured in the fixed variables. We included random intercepts that vary across households and clusters. The household-level random intercept captured the effect of latent household-specific covariates that cause some households to be more similar than others. Cluster-level unobserved characteristics, such as cultural norms, were captured by the cluster random-effect. The choice of cluster and household level random effects was informed by intracommunity correlation coefficient tested at the zonal, cluster and household level. Therefore, all four multilevel logistic regression models contained fixed effects and random effects with three levels, clusters at level 1, households at level 2 and individuals (woman–baby dyads) at level 3. We considered variables to be highly correlated if they had a coefficient of over 0.80 based on Pearson correlation coefficient.

Analyses were conducted in Stata/SE V.15. In all analyses, we adjusted for survey design (*svyset* with clusters, individual sampling weights and stratification). There was no missingness in the urbanicity measure, the main outcomes or other key confounders. There was substantial missingness in the birth weight variable, largely because women reported that their newborns were not weighed.

Patient and public involvement

Patients and/or the public were not involved in the design, conduct, reporting or dissemination of this research.

RESULTS

Geographical classification of clusters

Mainland Tanzania DHS 2015–2016 contained 527 clusters. Based on the GHS-SMOD urbanicity measure, 61 (11.6%) were core urban, 224 (42.5%) semi-urban and 242 (45.9%) rural. The comparison of DHS and GHS-SMOD classification of clusters is shown in table 1. All the core urban clusters were correctly identified as urban by DHS. However, there were discrepancies in the other two classes. Among the 224 semi-urban clusters, 138 were reported by DHS as rural and 86 as urban, while among the 242 GHS-SMOD rural clusters, 226 were identified by DHS as rural while 16 were identified as urban. It is expected that the semi-urban classes contain a mixture of urban and rural cells. However, 16 rural clusters were misclassified by the DHS as urban although 13 of these clusters (81%) had the majority of the pixels within their buffers as very low-density rural pixels and 9 of these clusters (56%) had maximum values of either 1 or 2. Therefore, these 16 clusters had a very high likelihood of being truly rural.

Travel time to nearest hospital

The average travel time from each cluster to the nearest public hospital was 63 min, with large subnational variations at high spatial resolution. At cluster level, modelled travel time estimates ranged between 0 and 418 min (7 hours). Among the 527 included clusters, 349 (66%) were within a 1-hour catchment of the nearest public hospital, while 23% (121 clusters) were within 2–3 hours (online supplemental file 1). Stratification by urbanicity showed that the DHS rural and urban classes had an average of 14 and 78 min of travel time to the nearest hospital, respectively. In the three new urbanicity classes, the average travel time was 89 min in rural clusters, 41 min in semi-urban clusters and 4 min in core urban clusters. Majority of semi-urban and core urban clusters were within 30 min of the nearest public hospital (figure 1).

Description of the sample

The analysis data set contained 8915 pregnancies of 7 or more months among 6156 unique women: 3765 women contributed one pregnancy, 2042 women contributed two pregnancies, 330 women contributed three pregnancies and 19 women contributed four pregnancies. Among these 8915 pregnancies, 8739 resulted in live births and 176 in stillbirths. Among the live births, 217

Table 1 DHS Tanzania 2015–2016 mainland clusters based on DHS versus GHS-SMOD classification

		GHS-SMOD urbanicity classes			
		Core urban	Semi-urban	Rural	Total
DHS residence	Rural	0	138	226	364
	Urban	61	86	16	163
Total		61	224	242	527

DHS, Demographic and Health Surveys; GHS-SMOD, Global Human Settlement Layer-settlement model .

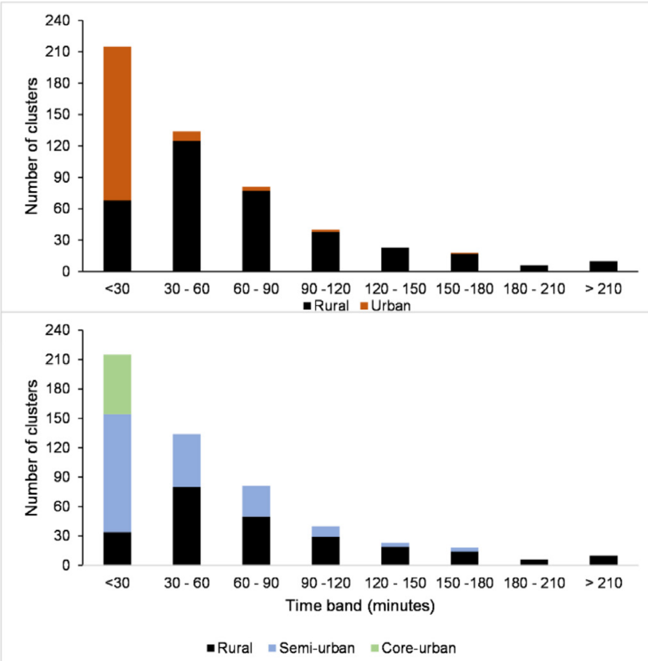

Figure 1 Distribution of 527 clusters in mainland Tanzania by travel time to nearest public hospital in minutes by the Demographic and Health Surveys (top panel) and Global Human Settlement Layer-settlement model (bottom panel) urban classification of clusters.

neonatal deaths were reported (180 early neonatal and 37 late neonatal). A total of 356 perinatal deaths (stillbirths+early neonatal deaths) were reported. Table 2 shows the distribution of the outcome variables and the characteristics of the analysis subgroups based on availability of variables, for Tanzania mainland overall and by GHS-MOD urbanicity categories. More than half of all births in the sample occurred in core urban or semi-urban areas.

Neonatal and perinatal mortality

Table 3 presents the neonatal and perinatal mortality rates by DHS residence, GHS-SMOD urbanicity classification and for mainland Tanzania overall. The comparison shows that mortality estimates for rural areas did not differ between DHS and GHS-SMOD classifications. The perinatal and neonatal mortality rates in the new urbanicity class of semi-urban were similar to levels in rural categories of both DHS and GHS-SMOD. Within the GHS-SMOD classification, core urban areas reached the highest perinatal (56.4/1000 pregnancies) and neonatal mortality rates (39.8/1000 live births); these were significantly higher than those observed in semi-urban and rural areas.

Further details of neonatal and perinatal mortality are shown in online supplemental file 3. Briefly, among the 217 neonatal deaths, the distribution of timing of death was significantly different by urbanicity. In core urban clusters, more than 95% of neonatal deaths occurred in the first week of life (predominantly on days 2–7), compared with 19% in semi-urban and 14% in rural areas. However, within the early neonatal period, semi-urban and rural areas had a higher percentage of deaths on day of birth compared with core urban areas. The mean age at death was 4.1 days; this was shortest in the core urban category of clusters (2.9 days) compared with semi-urban (5.1) and rural (3.6). Among the 73 most recent neonatal deaths of babies born in facilities, we looked at whether the death occurred before or after discharge from the facility. Two-fifths of neonatal deaths in core urban and rural clusters occurred after discharge; this was much higher (73%) in semi-urban areas, a significant difference despite the small sample size; but corresponding with the results on distribution of time of death. We also examined the ratio of stillbirths to early neonatal deaths which is a proxy for misclassification between the two outcomes and stillbirth data quality. The ideal ratio should be around 1.2 with much lower or higher values indicating possible under-reporting or misclassification.[25] Overall, among all areas in Tanzania the ratio was 0.85 indicating a small degree of under-reporting. However, when examined according to urbanicity status, core urban areas had the most under-reporting or misclassification of stillbirths with a ratio of 0.52 compared with semi-urban and rural areas which had reasonably good ratios just below 1.

Bivariate analysis

Bivariate analysis examining the association of variables with neonatal death and perinatal death is shown in table 4. Compared with GHS-SMOD rural class, the odds of death were not higher in semi-urban areas, but were significantly higher in core urban areas (OR=1.85, 95% CI 1.12 to 3.08) for neonatal death and 1.60 (95% CI 1.2 to 2.3) for perinatal death. Compared with the Lake zone, only Southern and Eastern zones had significantly different (higher) neonatal and perinatal mortality. Women from richer households and more educated women had higher odds of reporting neonatal mortality compared with women from poorer households and without formal education. Age and maternal anaemia were associated with both neonatal and perinatal death. Among live births, the crude odds of neonatal death was higher for caesarean mode of delivery, multiple births, primiparous mothers, male newborns, hospital births and lack of ANC during pregnancy. Among newborns who were weighed, both low birth weight and macrosomia were associated with higher odds of neonatal mortality compared with normal birth weight.

Multivariable analysis

Table 5 shows the results of the four multivariable models. Overall, these models show that the adjusted odds of neonatal death in core urban areas was between 26% and 136% higher, and in semi-urban areas 26%–77% higher compared with rural areas. The adjusted odds of perinatal death in core urban areas were 71% higher and in semi-urban areas 8% higher compared with rural areas. The direction of association was consistent across the four models, but in none of them was it significant at the p<0.05 level.

Table 2 Characteristics of pregnancies and births in analysis, overall and by urbanicity class

Numbers of observations		Total		Core urban		Semi-urban		Rural	
Live births in last 5 years		8739		692		3597		4450	
Most recent live births in last 5 years		6099		560		2544		2995	
Total births in last 5 years (live births and stillbirths)		8915		707		3671		4537	
Neonatal deaths within last 5 years		217		26		94		97	
Early neonatal deaths within last 5 years		180		25		72		83	
Stillbirths within last 5 years		176		15		74		87	
Perinatal deaths in last 5 years (early neonatal deaths and stillbirths)		356		40		146		170	
Part A: All births (n=8915)		**Total**		**Core urban**		**Semi-urban**		**Rural**	
		n	**Column %**	**n**	**Column %**	**n**	**Column %**	**n**	**Column %**
Urbanicity class	Core urban	707	*11.7*						
	Semi-urban	3671	*39.5*						
	Rural	4537	*48.8*						
Geographical zone	Western	979	*12.4*	50	*4.1*	322	*9.9*	607	*16.5*
	Lake	2929	*32.7*	123	*16.3*	1535	*41.9*	1271	*29.2*
	Northern	770	*9.5*	108	*16.4*	312	*9.4*	350	*8.0*
	Central	1010	*11.4*	0	*0.0*	247	*7.4*	763	*17.3*
	Southwest highlands	1149	*9.9*	35	*4.6*	504	*9.1*	610	*11.8*
	Southern highlands	734	*5.5*	5	*0.4*	299	*6.1*	430	*6.3*
	Southern	418	*4.1*	5	*0.6*	148	*3.9*	265	*5.1*
	Eastern	926	*14.5*	381	*57.6*	304	*12.3*	241	*5.8*
Household wealth quintile	Poorest	2355	*24.7*	3	*0.6*	595	*14.7*	1757	*38.5*
	Poorer	1978	*21.5*	2	*0.3*	728	*20.4*	1248	*27.6*
	Middle	1766	*19.5*	13	*1.7*	830	*23.4*	923	*20.5*
	Richer	1594	*18.4*	148	*22.0*	913	*25.3*	533	*11.9*
	Richest	1222	*15.9*	541	*75.4*	605	*16.2*	76	*1.5*
Maternal education and literacy	No education	1899	*21.0*	42	*6.5*	658	*17.4*	1199	*27.3*
	Primary education/ illiterate	988	*10.6*	45	*6.6*	418	*10.9*	525	*11.4*
	Primary education/ literate	4921	*55.3*	375	*53.5*	2051	*56.8*	2498	*54.6*
	Secondary or higher	1107	*13.1*	248	*33.4*	544	*14.9*	315	*6.7*
Marital status	Married or cohabiting	7388	*82.5*	551	*78.1*	2939	*79.8*	3898	*85.6*
	Not married or cohabiting	1527	*17.5*	156	*21.9*	732	*20.2*	639	*14.4*
Maternal age group (in years)	<20	1555	*17.8*	90	*13.4*	662	*18.3*	803	*18.5*
	20–29	4417	*49.5*	417	*58.7*	1802	*48.3*	2198	*48.3*
	30–49	2943	*32.7*	200	*27.9*	1207	*33.4*	1536	*33.2*

Continued

Table 2 Continued

Numbers of observations		Total		Core urban		Semi-urban		Rural	
Maternal decision-making about health	Self (fully or partly)	6743	*75.6*	581	*81.8*	2809	*77.2*	3353	*72.8*
	Others	2172	*24.4*	126	*18.2*	862	*22.8*	1184	*27.2*
Maternal relocation (fewer than 5 years lived in current residence)	Yes	2275	*25.8*	432	*37.7*	2608	*27.9*	3600	*21.3*
	No	6640	*74.2*	275	*62.3*	1063	*72.1*	937	*78.7*
Maternal anaemia at survey	Yes	4000	*45.3*	311	*45.1*	1635	*44.9*	2054	*45.3*
	No	4915	*54.7*	396	*54.9*	2036	*55.1*	2483	*54.7*
Maternal mobile ownership	Yes	3958	*46.0*	600	*84.8*	1842	*50.7*	1516	*32.9*
	No	4957	*54.0*	107	*15.2*	1829	*49.3*	3021	*67.1*
Ownership of health insurance	Yes	670	*7.5*	73	*9.2*	319	*9.1*	278	*7.5*
	No	8245	*92.5*	634	*90.8*	3352	*90.9*	4259	*92.5*
Travel to nearest hospital (hours)	Less than 2 hours	7444	*87.8*	707	*100.0*	3474	*97.3*	3429	*77.1*
	Two hours or more	1471	*12.2*	0	*0*	197	*2.7*	1108	*22.9*
		Mean	**SE**	**Mean**	**SE**	**Mean**	**SE**	**Mean**	**SE**
Travel to nearest hospital (minutes)		59.6	3.6	4.7	0.50	38.1	2.40	90.0	6.30
Household size (mean number of members)		7.2	0.14	5.8	0.20	7.1	0.17	7.6	0.26
Part B: Additional variables available for all live births (n=8739)									
		n	**Column %**	**n**	**Column %**	**n**	**Column %**	**n**	**Column %**
Mode of delivery	Vaginal	8263	94.1	589	84.8	3398	94.2	4276	96.2
	Caesarean	476	5.9	103	15.2	199	5.8	174	3.8
Multiple birth	Yes	297	3.6	28	4.8	129	3.3	140	3.6
	No	8442	96.4	664	95.2	3468	96.7	4310	96.4
Birth order and preceding birth interval (months)	First child	2094	24.7	244	35.0	883	24.7	967	22.2
	Second/third; <24	568	6.3	40	5.9	233	6.2	295	6.6
	Second/third; 24+	2345	27.8	275	40.4	1011	28.3	1059	24.4
	Fourth+; <24	712	7.7	18	2.2	262	7.4	432	9.2
	Fourth+; 24+	3020	33.5	115	16.5	1208	33.4	1697	37.6
Sex of child	Male	4438	49.2	370	46.8	1826	51.0	2242	50.0
	Female	4301	50.8	322	53.2	1771	49.0	2208	50.0
Pregnancy wanted at the time	Yes	6092	69.4	481	69.3	2419	66.9	3192	71.6
	No	2647	30.6	211	30.7	1178	33.1	1258	28.4
Place of birth	Home	3336	37.5	48	6.6	1166	31.9	2122	49.4
	Lower-level facility	2750	30.6	157	25.1	1174	32.1	1419	30.7
	Hospital	2653	31.9	487	68.3	1257	36.0	909	19.9
Part C: Additional variables available for most recent live births (n=6099)**									
Antenatal care during pregnancy	No ANC	124	2.0	11	1.7	34	1.4	79	2.7
	1–3 visits	2981	47.3	160	26.9	1283	49.3	1538	51.5
	4 or more visits	2994	50.7	389	71.4	1227	49.3	1378	45.8

Continued

Table 2 Continued

Numbers of observations		Total		Core urban		Semi-urban		Rural	
Child weighed at birth	Yes	4050	67.5	537	96.1	1842	73.2	1671	54.3
	No	2049	32.5	23	3.9	702	26.8	1324	45.7
Part D: Additional variable available for most recent live births whose birth weight was taken (n=4050)**									
Child's birth weight category (in grams)	Low (<2500 g)	248	6.2	40	7.3	109	6.0	99	5.8
	Normal (2500–4000 g)	3547	87.7	473	88.7	1609	87.0	1465	88.0
	Macrosomia (>4000 g)	255	6.1	24	4.0	124	7.0	107	6.2

*Child's birth weight is available for all live births but we restricted to most recent live births to improve accuracy of recall and flow of analysis subsamples.
ANC, antenatal care.

DISCUSSION

We found a consistent pattern of higher odds of neonatal and perinatal death with increasing levels of urbanicity in mainland Tanzania, which was particularly pronounced in densely populated core urban areas. The category of semi-urban areas had levels of neonatal and perinatal mortality similar to rural areas. However, the multivariable associations were not significant at the p<0.05 level, most likely due to a small sample size of neonatal and perinatal deaths. Taken together with previous studies,[6] these findings bolster our confidence in the evidence showing an association between higher levels of urbanicity and higher neonatal and perinatal mortality.

In terms of the exposure, satellite imagery-based urbanicity categories captured the meaning of urbanicity more accurately than the DHS urban/rural residence. The most important cause of misclassification between the two methods was that some clusters considered urban by DHS were rural according to GHS-SMOD. Much of the existing research frames urban areas as a monolith, but urban areas are not homogenous, and most studies are not able to differentiate between peri-urban and suburban areas, areas of informal settlements, urban slums or affluent parts of cities and ignore variations within a single city. There is no uniform definition of an urban area. The DHS relies on the country's definition of urban/rural which is variable between countries and across time. Statistical offices across countries use population thresholds of a settlement or a combination of population size and the proportion of residents employed in agriculture to define an urban area.[26] Specifically in Tanzania, the definition of urban areas is based on all regional and district headquarters and wards with urban characteristics.[27] Urban wards have above a specified population density and/or a certain percentage of residents in non-agricultural occupations. Consequently, many studies rely on categorisations of urbanicity based on national administrative definitions that are not always an accurate reflection of reality. This is due partly to (1) lack of use of standard criteria, (2) lack of re-evaluation and recategorisation of areas over time and (3) the possible political influence on the categorisation (eg, redefining an area as urban may trigger different requirements regarding government allocation of resources or infrastructure).[28 29]

We discuss several findings from our study to expound potential mechanisms underlying this association between urbanicity and neonatal and perinatal mortality.

Table 3 Neonatal and perinatal mortality rates by DHS urban/rural residence and GHS-SMOD urbanicity categories, with 95% CI in mainland Tanzania

DHS residence	Overall (Tanzania mainland)	Urban	Rural	P value
Perinatal mortality (per 1000 pregnancies of 7 months and more)	39.1 (34.8 to 43.9)	46.9 (38.3 to 57.3)	36.2 (31.4 to 41.7)	0.0387
Neonatal mortality (per 1000 live births)	25.1 (21.3 to 29.6)	38.6 (30.2 to 49.3)	20.1 (16.2 to 24.9)	<0.001
GHS-SMOD urbanicity class	**Core urban**	**Semi-urban**	**Rural**	**P value**
Perinatal mortality (per 1000 pregnancies of 7 months and more)	56.4 (41.5 to 76.2)	37.9 (31.2 to 46.0)	35.9 (30.6 to 42.2)	0.0277
Neonatal mortality (per 1000 live births)	39.8 (26.3 to 59.9)	24.8 (19.6 to 31.4)	21.9 (16.8 to 28.5)	0.0371

DHS, Demographic and Health Surveys; GHS-SMOD, Global Human Settlement Layer-settlement model .

Table 4 Bivariate associations with neonatal death and perinatal death

		Neonatal death (n=217)			Perinatal death (n=393)		
		OR	95% CI	P value	OR	95% CI	P value
		n=8739 (all live births)			n=8915 (all births)		
Urbanicity class	Core urban	1.85	1.12 to 3.08	0.017	1.6	1.12 to 2.3	0.011
	Semi-urban	1.13	0.8 to 1.62	0.476	1.06	0.82 to 1.37	0.67
	Rural	Ref			Ref		
Geographical zone	Western	1.06	0.58 to 1.96	0.837	0.88	0.58 to 1.32	0.532
	Lake	Ref			Ref		
	Northern	0.93	0.47 to 1.84	0.838	0.88	0.51 to 1.51	0.65
	Central	1.32	0.71 to 2.47	0.385	1.05	0.67 to 1.64	0.837
	Southwest highlands	1.55	0.84 to 2.84	0.158	1.06	0.69 to 1.63	0.797
	Southern highlands	1.5	0.77 to 2.91	0.23	1.06	0.68 to 1.67	0.788
	Southern	2.19	1.13 to 4.25	0.021	2.11	1.34 to 3.14	0.001
	Eastern	2.01	1.18 to 3.43	0.01	1.46	1 to 2.13	0.048
Household wealth quintile	Poorest	Ref			Ref		
	Poorer	1.52	0.92 to 2.51	0.103	1.24	0.84 to 1.82	0.287
	Middle	1.11	0.66 to 1.86	0.702	1.38	0.97 to 1.98	0.076
	Richer	1.81	1.08 to 3.04	0.024	1.43	0.97 to 2.11	0.068
	Richest	2	1.16 to 3.43	0.012	1.42	0.94 to 2.12	0.092
Maternal education and literacy	No education	Ref			Ref		
	Primary education/illiterate	2	1.05 to 3.81	0.036	1.34	0.84 to 2.15	0.215
	Primary education/literate	2.34	1.46 to 3.73	<0.001	1.52	1.09 to 2.12	0.014
	Secondary or higher	2.25	1.25 to 4.05	0.007	1.23	0.8 to 1.9	0.352
Marital status	Married or cohabiting	Ref			Ref		
	Not married or cohabiting	1.24	0.87 to 1.78	0.234	1.23	0.91 to 1.66	0.177
Maternal age group (in years)	<20	1.53	1.02 to 2.3	0.041	1.5	1.08 to 2.1	0.017
	20–29	Ref			Ref		
	30–49	1.08	0.71 to 1.65	0.704	1.09	0.81 to 1.44	0.571
Maternal decision-making about health	Self (fully or partly)	Ref			Ref		
	Others	1.02	0.68 to 1.54	0.918	1.15	0.85 to 1.56	0.366
Maternal relocation (<5 years lived in current residence)	Yes	1.15	0.78 to 1.7	0.468	1.07	0.8 to 1.43	0.663
	No	Ref			Ref		
Maternal anaemia at survey	Yes	1.36	1 to 1.84	0.049	1.35	1.07 to 1.7	0.011
	No	Ref			Ref		
Maternal mobile ownership	Yes	1.24	0.9 to 1.72	0.187	1.06	0.83 to 1.35	0.632
	No	Ref			Ref		
Ownership of health insurance	Yes	1.41	0.78 to 2.53	0.258	1.15	0.68 to 1.94	0.591
	No	Ref			Ref		
Travel to nearest hospital (hours)		0.92	0.75 to 1.13	0.425	0.97	0.86 to 1.1	0.675
Number of household members		0.9	0.83 to 0.97	0.005	0.92	0.87 to 0.97	0.002
Mode of delivery	Vaginal	Ref					
	Caesarean	2.22	1.3 to 3.79	0.003			
Multiple birth	Yes	5.4	3.08 to 9.45	<0.001			
	No	Ref					

Continued

Table 4 Continued

		Neonatal death (n=217)			Perinatal death (n=393)		
		OR	95% CI	P value	OR	95% CI	P value
Birth order and preceding birth interval (months)	First child	2.1	1.38 to 3.16	<0.001			
	Second/third; <24	1.25	0.57 to 2.77	0.575			
	Second/third; 24+	Ref					
	Fourth+; <24	1.72	0.96 to 3.05	0.066			
	Fourth+; 24+	1.22	0.76 to 1.96	0.403			
Sex of child	Male	1.41	1.02 to 1.95	0.04			
	Female	Ref					
Pregnancy wanted at the time	Yes	Ref					
	No	0.78	0.55 to 1.13	0.187			
Place of birth	Home	Ref					
	Lower-level facility	1.3	0.87 to 1.93	0.198			
	Hospital	1.76	1.19 to 2.59	0.005			
		n=6099 (most recent live births)					
Antenatal care during pregnancy	No ANC	3.32	1.14 to 9.64	0.028			
	1–3 visits	1.13	0.73 to 1.76	0.587			
	4 or more visits	Ref					
Child weighed at birth	Yes	0.76	0.48 to 1.22	0.255			
	No	Ref					
		n=4050 (most recent live births with weight available)					
Child's birth weight category (in grams)	Low (<2500 g)	5.34	2.62 to 10.88	<0.001			
	Normal (2500–4000 g)	Ref					
	Macrosomia (>4000 g)	2.77	1.12 to 6.88	0.028			

Grey shading—variable not available for all observations.
ANC, antenatal care .

A recent paper on the reasons for loss of urban mortality advantage among adults (15–49 year olds) from multiple DHS surveys using the urban/rural stratification noted that rapid expansion of population in slums has led to premature mortality linked to overcrowding, poverty, road traffic accidents, lack of sanitation and the double burden of malnutrition leading to non-communicable diseases in this population.[5] On the other hand, they described an urban advantage in child survival, which they attributed in part to better access to healthcare, better infrastructure, greater economic opportunities and other factors such as lower fertility levels and longer birth intervals. Causes of stillbirths and deaths in the neonatal period are a combination of the various factors affecting the health of adults in general and pregnant women in particular (eg, maternal nutrition, exposure to infections such as sexually-transmitted infections and malaria, occupational hazards, exposure to heat and pollution), as well as that of children (access to healthcare and the quality of that care, particularly at time of labour and birth).

Multiple causal pathways for the effect of urban residence on neonatal survival have been proposed, including individual health-seeking behaviour/accessibility of care, obstetrical risk factors, quality of care during pregnancy, childbirth and the postnatal period, as well as broader issues related to socioeconomic determinants, urban living conditions and urbanisation processes.[6] Our multivariable models included variables capturing all these four dimensions. While some of these were significantly associated with neonatal and perinatal mortality, their inclusion did not completely explain the association between urbanicity and neonatal/perinatal mortality. We highlight several findings which could inform future analyses to explore the causal pathways in more depth.

Issues linked to access to care and care quality in urban areas are numerous. The use of ANC and facility-based childbirth care in large cities in Africa is near-universal (>94% in Dar es Salaam), but characterised by high levels of private sector use and inconsistent receipt of evidence-based interventions.[30] The analysis of 22 large African cities also showed variable levels of essential care elements

Table 5 Multivariable associations with neonatal death and perinatal death (four models)

Model	1			2			3			4		
Outcome	Neonatal death (n=217)			Neonatal death (n=97)			Neonatal death (n=60)			Perinatal death (n=356)		
Sample	All live births (n=8739)			Most recent live births (n=6099)			Most recent live births with birth weight (n=4050)			All births (n=8915)		
	aOR	95% CI	P value	aOR	95% CI	P value	aOR	95% CI	P value	aOR	95% CI	P value
Urbanicity class												
Core urban	1.26	0.57 to 2.79	0.568	1.52	0.3 to 7.75	0.615	2.36	0.69 to 8.04	0.17	1.71	0.89 to 3.27	0.106
Semi-urban	1.26	0.79 to 2.01	0.323	1.77	0.71 to 4.4	0.22	1.66	0.74 to 3.77	0.222	1.08	0.77 to 1.53	0.653
Rural	Ref			Ref			Ref			Ref		
Geographical zone												
Western	1.51	0.71 to 3.21	0.287	0.82	0.19 to 3.6	0.789	1.5	0.39 to 5.75	0.557	1.04	0.61 to 1.75	0.895
Lake	Ref			Ref			Ref			Ref		
Northern	0.78	0.33 to 1.82	0.566	0.64	0.15 to 2.72	0.542	1.43	0.42 to 4.83	0.566	0.74	0.41 to 1.34	0.322
Central	1.41	0.67 to 3.01	0.362	1.12	0.29 to 4.3	0.874	2.62	0.82 to 8.4	0.105	1.06	0.63 to 1.8	0.826
Southwest highlands	1.4	0.65 to 3.06	0.39	0.83	0.2 to 3.42	0.799	1.04	0.27 to 4.02	0.95	0.96	0.55 to 1.67	0.876
Southern highlands	1.41	0.59 to 3.39	0.439	0.61	0.12 to 3.05	0.549	0.86	0.2 to 3.57	0.831	1.02	0.53 to 1.95	0.95
Southern	2.2	0.88 to 5.51	0.094	1.81	0.38 to 8.68	0.455	0.83	0.18 to 3.89	0.817	2.21	1.2 to 4.07	0.011
Eastern	1.57	0.75 to 3.28	0.227	1.08	0.28 to 4.13	0.915	1.49	0.49 to 4.53	0.481	1.16	0.7 to 1.94	0.564
Household wealth quintile												
Poorest				Ref			Ref			Ref		
Poorer				1.76	0.5 to 6.17	0.378	1.3	0.4 to 4.26	0.667	1.21	0.76 to 1.91	0.417
Middle				2.29	0.65 to 8.07	0.196	1.97	0.62 to 6.27	0.253	1.45	0.91 to 2.31	0.118
Richer				1.33	0.33 to 5.32	0.685	1.53	0.47 to 5.08	0.481	1.24	0.75 to 2.05	0.411
Richest				1.37	0.26 to 7.34	0.71	1.22	0.31 to 4.81	0.779	0.93	0.49 to 1.75	0.818
Maternal education and literacy												
No education	Ref			Ref			Ref					
Primary education/illiterate	1.81	0.8 to 4.1	0.154	4.33	0.99 to 19.02	0.052	3.91	1.06 to 14.48	0.041			
Primary education/literate	1.95	1.06 to 3.6	0.032	2.91	0.9 to 9.46	0.075	3.84	1.26 to 11.78	0.018			
Secondary or higher	1.43	0.63 to 3.25	0.393	1.69	0.36 to 8.01	0.506	4.06	1.03 to 16.01	0.045			
Maternal age group (in years)												
<20	1.44	0.8 to 2.61	0.224	3.69	1.37 to 9.95	0.01	1.76	0.67 to 4.66	0.253	1.76	1.23 to 2.5	0.002
20–29	Ref			Ref			Ref			Ref		
30–49	1.23	0.73 to 2.1	0.436	3.4	1.46 to 7.96	0.005	1.18	0.6 to 2.35	0.63	1.27	0.92 to 1.75	0.149

Continued

Table 5 Continued

Model	1			2			3			4		
Outcome	Neonatal death (n=217)			Neonatal death (n=97)			Neonatal death (n=60)			Perinatal death (n=356)		
Sample	All live births (n=8739)			Most recent live births (n=6099)			Most recent live births with birth weight (n=4050)			All births (n=8915)		
	aOR	95% CI	P value	aOR	95% CI	P value	aOR	95% CI	P value	aOR	95% CI	P value
Maternal anaemia at survey												
Yes	1.48	0.99 to 2.21	0.058							1.44	1.07 to 1.92	0.015
No	Ref									Ref		
Maternal mobile ownership												
Yes							0.65	0.34 to 1.21	0.174			
No							Ref					
No. of household members	0.89	0.83 to 0.96	0.002	0.79	0.68 to 0.92	0.002	0.8	0.7 to 0.9	<0.001	0.92	0.88 to 0.96	<0.001
Mode of delivery												
Vaginal	Ref			Ref								
Caesarean	1.7	0.87 to 3.36	0.123	2.39	0.71 to 8.07	0.161						
Multiple birth												
Yes	14.97	7.25 to 30.89	<0.001	11.15	1.98 to 62.67	0.006						
No	Ref			Ref								
Birth order and preceding birth interval (months)												
First child	2.15	1.21 to 3.85	0.01				0.43	0.18 to 1.05	0.064			
Second/third; <24	0.57	0.24 to 1.37	0.207				0.29	0.04 to 2.2	0.23			
Second/third; 24+	Ref						Ref					
Fourth+; <24	2.11	0.97 to 4.58	0.061				3.48	1.07 to 11.24	0.037			
Fourth+; 24+	1.18	0.64 to 2.16	0.595				1.87	0.85 to 4.12	0.119			
Sex of child												
Male	1.91	1.32 to 2.75	0.001				2.32	1.32 to 4.06	0.003			
Female	Ref						Ref					
Place of birth												
Home	Ref			Ref			Ref					
Lower-level facility	1.03	0.63 to 1.69	0.898	1.37	0.51 to 3.67	0.527	6.08	0.54 to 68.34	0.144			
Hospital	1.25	0.74 to 2.12	0.41	2.09	0.75 to 5.84	0.159	8.2	0.73 to 91.92	0.088			
Pregnancy wanted at the time												
Yes				Ref			Ref					

Continued

Table 5 Continued

Model	1			2			3			4		
Outcome	Neonatal death (n=217)			Neonatal death (n=97)			Neonatal death (n=60)			Perinatal death (n=356)		
Sample	All live births (n=8739)			Most recent live births (n=6099)			Most recent live births with birth weight (n=4050)			All births (n=8915)		
	aOR	95% CI	P value	aOR	95% CI	P value	aOR	95% CI	P value	aOR	95% CI	P value
No				0.56	0.26 to 1.22	0.144	0.77	0.42 to 1.42	0.408			
Antenatal care during pregnancy												
No ANC				25.65	4.02 to 163.33	0.001	3.13	0.33 to 29.65	0.319			
1–3 visits				1.36	0.66 to 2.79	0.406	1.87	1.08 to 3.26	0.026			
4 or more visits				Ref			Ref					
Child's birth weight category												
Low (<2500 g)							9.69	4.45 to 21.11	<0.001			
Normal (2500–4000 g)							Ref					
Macrosomia (>4000 g)							3.79	1.62 to 8.89	0.002			
Random effects												
Household and cluster (variance and SE)	5.32 (0.88)			11.62 (3.08)			2.04 (0.77)*			3.71 (0.52)		

Variable not included.
Variable not available for all observations.
*Model 3 frandom effects included clusters only as due to small sample size of outcomes, the model with both cluster and household did not converge.
ANC, antenatal care ; aOR, adjusted OR.

(>99% of babies born in health facilities were weighed but only half of babies initiated breast feeding within an hour of birth) and high levels of early discharge from health facilities following both vaginal and caesarean section births in Dar es Salaam. Further, literature shows that poor women, especially those living in informal settlements, might also receive poorer quality of care, encounter stigmatising attitudes and disrespectful care in health facilities.[31–33] Our additional analysis on the timing of deaths showed that a comparatively low percentage of neonatal deaths in core urban areas occurred on the day of birth compared with semi-urban and rural areas. Interpretation is difficult, but one explanation may be better access to emergency obstetrical care including neonatal resuscitation in core urban compared with rural areas.[34] Some resuscitated babies may still die a few days later because of underlying conditions due to complications of preterm birth, infections and late complications from asphyxia.

The high degree of under-reporting of stillbirths in the core urban area points to potential misclassification of stillbirths as neonatal deaths or general under-reporting of stillbirths in these contexts. Misclassification in household surveys has been reported in several studies.[10 35–37] That this pattern appears largely confined to urban areas in our study warrants further investigation. We would expect better differentiation between these outcomes in an urban setting where higher quality services and more skilled personnel are available. Another contributing factor could be the impact of recent training on neonatal resuscitation in several health facilities in these areas which may be improving the survival of babies thus leading to fewer stillbirths. The three models looking at neonatal mortality showed a consistent association between higher levels of education and *higher* neonatal mortality. This is unlikely to be a result of confounding by older maternal age (which is linked to poorer perinatal survival[38]) because age was included in the multivariable models. One possible explanation is that the extent of under-reporting of neonatal deaths is higher among women with no education because of stigma,[39] thus artificially increasing the odds of mortality among those with higher levels of education.

Higher number of household members was consistently and significantly associated with lower adjusted odds of neonatal and perinatal mortality. We estimate that for every additional household member, the odds of neonatal and perinatal mortality declined by approximately 10%. This points to the importance of familial support including advocating and enabling timely care-seeking (eg, by recognising danger signs, providing childcare during woman's absence or assisting during travel), help within the household and with enabling positive behaviours such as self-care and breast feeding.[40] The availability of such support is likely lower for women residing in urban areas. In addition, we identified several known biological risk factors which are linked to increased neonatal and perinatal mortality in the absence of accessible, high-quality care. These include young and older maternal age, maternal anaemia, male sex of newborn, multiplicity, first birth and birth after a short birth interval. It is possible that the manner in which these known and yet unknown risk factors operate is different in densely populated urban settings compared with rural areas. While the sample size available on the DHS did not allow us to test for interactions, we note that improving access to good quality care both during pregnancy and at the time of birth is essential for preventing neonatal and perinatal deaths.

Strengths and limitations

Our in-depth analysis of the association between urban residence and neonatal and perinatal mortality addressed several critical limitations of previous studies. We were able to more accurately classify the gradient of urbanicity[41] based on data that incorporates satellite imagery, built environment and population density, rather than on administrative delineation. By disaggregating urbanicity to core urban and semi-urban we more accurately captured the variation in human settlement on a continuum and exposed any dose-response associations. However, our indicator of urbanicity has limitations, including grouping affluent parts together with slums or informal settlements in core urban areas. The alternative could have been to use a composite measure combining wealth quintile and urbanicity to construct a fourth category referring to slums and informal settlements—proxied by the poorest quintiles living in core urban areas slums.[42] However, sample size constraints of the main outcomes made this approach unfeasible.

By including the two outcomes of neonatal mortality and perinatal mortality, we addressed some misclassifications between stillbirth and neonatal deaths. However, our data indicate that neonatal and perinatal deaths are under-reported in these survey self-reports, in view of the implausible higher neonatal mortality in better educated and more wealthy groups. Many key variables on pregnancy and birth, such as place and mode of birth, were not available for pregnancies resulting in stillbirths.[43] Also, other key confounders were not available, meaning that none of the four models were theoretically complete.

Limitations also exist in several other variables. Travel time was based on the nearest public hospital, whereas in reality, women often bypass the nearest facility.[44 45] Further, we made assumptions about travel speed, which may not hold true in all places and might have a larger margin of error within cities due to, for example, variability in traffic and weather, and waiting time.[46] However, this was necessary due to lack of observational data.[47] The exact location of the household of residence for each woman is obscured by provision of one cluster location and by cluster displacement in DHS due to reasons of anonymity. We tried to ameliorate this by including some cluster level variables which would tell us about the lived environment of the 'neighbourhood'. Additionally, we did not have a variable accounting for daily mobility of people in and out of urban areas during the day due to lack of such data.

Our Model 3 did not have fixed effects for households, instead additional key variables (birth weight and number of ANC visits) captured some differences between the households that were being captured by the random effect. The data excludes babies born to women who subsequently died themselves. Finally, even though the DHS is a nationally representative survey and the number of women interviewed had increased in recent years, the sample size of neonatal deaths and stillbirths was relatively small. The limited sample size could be one reason why we did not detect a significant association between urbanicity and mortality in the multivariable results.

CONCLUSION

In our advanced analysis which improved the accuracy of the exposure variable (urbanicity), reduced reporting bias in outcome (by adding stillbirths) and adjusted for confounding and clustering more completely, we found moderate evidence of higher neonatal and perinatal mortality in semi-urban and particularly in core urban areas compared with rural areas in mainland Tanzania. The effect seemed to follow a dose-response pattern with increasing extent of urbanicity. This is consistent with earlier findings, and might extend to other countries with slower neonatal mortality declines in urban areas. Our multivariable analysis aimed to provide an in-depth understanding of the mechanisms of this association, however, we appreciate that many questions are still unanswered due to the data limitations. Therefore, we call for collection and analysis of more granular primary data to disentangle the contribution of pregnancy factors, living conditions and quality of care in birthing facilities.

Addressing the high rates of mortality in urban areas is also critical for Tanzania to meet the Sustainable Development Goals target on reduction of NMR to less than 16/1000 live births by 2030. Focusing solely or predominantly on rural areas is unlikely to tackle the high and largely preventable neonatal and perinatal mortality identified in urban areas, whether in the core, densely populated urban centres and particularly informal settlements or the growing semi-urban areas around Tanzania's main and secondary cities and towns. In order to appropriately target interventions, we must rely on more up-to-date, accurate and granular capture of urbanicity, which is possible through using innovative satellite technologies and spatial epidemiology approaches. We call for better data allowing disaggregation's into neighbourhoods of slums and informal settlements to ascertain whether across communities the 'urban' category is masking heterogeneities.

Author affiliations

[1]Population Health Unit, Kenya Medical Research Institute-Wellcome Trust Research Programme, Nairobi, Kenya
[2]Centre for Health Informatics, Computing and Statistics, Lancaster Medical School, Lancaster University, Lancaster, UK
[3]Department of Public Health, Institute of Tropical Medicine, Antwerpen, Belgium
[4]Social and Behavioral Sciences Research, Population Council, New York City, New York, USA
[5]Department of Obstetrics and Gynaecology, Muhimbili University of Health and Allied Sciences, Dar es Salaam, United Republic of Tanzania
[6]Department of Global Public Health, Karolinska Institutet, Stockholm, Sweden
[7]Department of Disease Control, Faculty of Infectious and Tropical Diseases, London School of Hygiene and Tropical Medicine, London, UK

Twitter Peter M Macharia @Pete_M_M, Lenka Beňová @lenkabenova and Aliki Christou @alichristou

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ORCID iDs
Peter M Macharia http://orcid.org/0000-0003-3410-1881
Lenka Beňová http://orcid.org/0000-0001-8595-365X
Jessie Pinchoff http://orcid.org/0000-0003-3155-595X
Aliki Christou http://orcid.org/0000-0001-9525-8255
Claudia Hanson http://orcid.org/0000-0001-8066-7873

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Supplementary file 1. Generating alternative classes of urbanicity by DHS cluster and modelling travel time to health facilities

As an alternative to the DHS urban and rural classifications, we derived three classes of the urban continuum (urbanicity) - rural, semi-urban, and core urban based on satellite imagery. We used the 2015 Global Human Settlement Layer- settlement model (GHS-SMOD)[1 2] to classify the location of DHS clusters into different degrees of urbanicity. GHS-SMOD delineates and classifies settlement typologies through cell clusters' population size, population, and built-up area densities based on the Built-up (GHS-BUILT) areas and Population (GHS-POP) data layers. GHS-BUILT represents the physical extent of the human settlement produced through automatic supervised classification of the Landsat and Sentinel satellite imagery while GHS-POP, a high spatial resolution (250x250 m^2 and 1x1 km^2) population density layer is produced by downscaling national census counts data at district level to a regular fine scale grid. It is the combination of GHS-BUILT and GHS-POP based on the *degree of urbanization* concept[3] that results in GHS-SMOD at the 1 km spatial resolution.[4]

Each pixel of the utilized GHS-SMOD layer[1] contained a single urbanicity class based on local population density, permanency of the water body, 30% or 50% of a pixel being built-up surface and generalization through smoothing and gap filling.[2] Based on these rules, level 1 encapsulates 3 classes (urban centre, urban cluster, and rural grid cell) which are further broken down (level 2) into seven classes that were used in this analysis namely; urban centre (class 30), dense urban cluster (class 23), semi-dense urban cluster (class 22), sub-urban or peri-urban (class 21), rural cluster (class 13), low density rural (class 12), very low-density rural (class 11), and water (class 10) grid cells. A detailed description of how these data are generated, processed, and classified is available elsewhere.[2 5] Supplementary file 1 shows the spatial distribution of the seven classes based on the 2015 GHS-SMOD layer in Tanzania describing the continuum from urban to rural areas in 2015. Urbanicity classes were first reclassified to an ordinal scale from 1 (least urban) to 7 (most urban) after masking out the water class. The average, majority, maximum and minimum values were extracted per buffer and used to define three new classes of urbanicity that were used for the bivariate and multi-level multivariate logistic regression analysis. Buffers were used to reduce the bias associated with scrambling cluster coordinates. We created 2km (urban clusters) and 5km (rural clusters) circular buffers and extracted the polygonal properties of urbanicity as previously implemented[6 7] and recommended.[8]

Due to the low count of neonatal deaths and homogeneity in some of the extracted urbanicity classes, the seven classes were collapsed into three classes based on the following criteria. Class 1 (core urban) where the mean of all cells per buffer was at least 6, and the maximum and majority of cells per buffer; Class 2 (semi-urban and areas in transition): The mean per buffer is 3 or above but less than 6, or the mean value was less than 3 but had a maximum of at least 4 or above to account for small elements of urban areas such as a small town surrounded by rural areas; the rest of the clusters were assigned to Class 3 (rural areas) that is, where all means were less than or equal to 2 while the maximum values per buffer were at least 4.

Modelling travel time to hospitals

Given that short distances in urban areas can obscure long travel times,[9] we also included a consideration for accessibility of emergency obstetric healthcare during pregnancy and childbirth generally provided only in hospitals as a potential explanation (effect moderator) between urbanicity and neonatal mortality. A proxy of geographic accessibility to hospital was not available in the DHS and was thus modelled independently for each cluster. It was proxied by the time taken to travel between a DHS cluster and the nearest public hospital, based on a least-cost path algorithm implemented in a Geographic Information System (GIS) via WHO AccessMod 5 software (alpha version 5.7.8)[10] widely used across healthcare applications in SSA.[11] We first assembled spatial layers of factors that affect travel time which included ESA Sentinel-2 landcover at 10m x 10m spatial resolution,[12] road network from OpenStreetMaps (OSM), NASA Shuttle Radar Topography Mission (SRTM) digital elevation model at 30m x 30m spatial resolution, water bodies and protected areas.[13] The land cover had nine classes (water, flooded vegetation, trees, ice/snow, grass, shrubs, crops, built-up areas and bare ground), while roads were re-classified into four classes (primary, secondary, tertiary, and minor roads) based on OSM description.

The spatial layers were resampled to 300m and merged to form a single layer via the *Accessibility module* in AccessMod software. Travel speeds were then applied on the merged layer to generate cumulative travel time from each cell (pixel) to the nearest hospital in mainland Tanzania at 300 x 300m spatial resolution. Two modes of transport were considered, walking while travelling on off-roads cells, and driving on motorable roads. The adopted modes and travel speeds across the different land cover and road classes were informed by previous studies in similar contexts.[14-16] Further, walking speeds were corrected for slope derived from DEM using Tobler's hiking function, an exponential function that describes how human walking speed varies with slope.[17] The base layer of hospitals was derived from a geolocated pan African master health facility list of public health service providers.[18] After verification, the list contained 236 public hospitals in Tanzania. The result was a gridded dataset showing travel time to the nearest public hospital in 2015 at 300m spatial resolution. We then linked each DHS cluster with its corresponding travel time to the nearest hospital. Similar to urbanicity, we extracted the average travel time as a continuous variable. For three clusters located in Maisome, Ikuza and Bulyalike islands we used reported travel times from co-author familiar with these regions (ABP). Modelled travel time was not available for these locations because we did not incorporate water as means of transport due to lack of data to parametrise the model.

Table S1: The mean travel time to the nearest hospital from each cluster stratified based on DHS (urban and rural) and GHS-SMOD (core urban, semi-urban and rural) classifications in Tanzania. The DHS and GHS-SMOD represents the same spatial extents

Source	Urban/rural classification	Number of clusters	Mean travel time (minutes)
DHS	Urban	163	14.4
	Rural	364	78.2
GHS-SMOD	Core urban	61	4.3
	Semi-urban	224	41.1
	Rural	242	89.4
National	8915	527	62.8

Figure S1. The spatial distribution of the seven classes based on the 2015 GHS-SMOD layer in Tanzania describing the continuum from urban to rural areas in 2015.

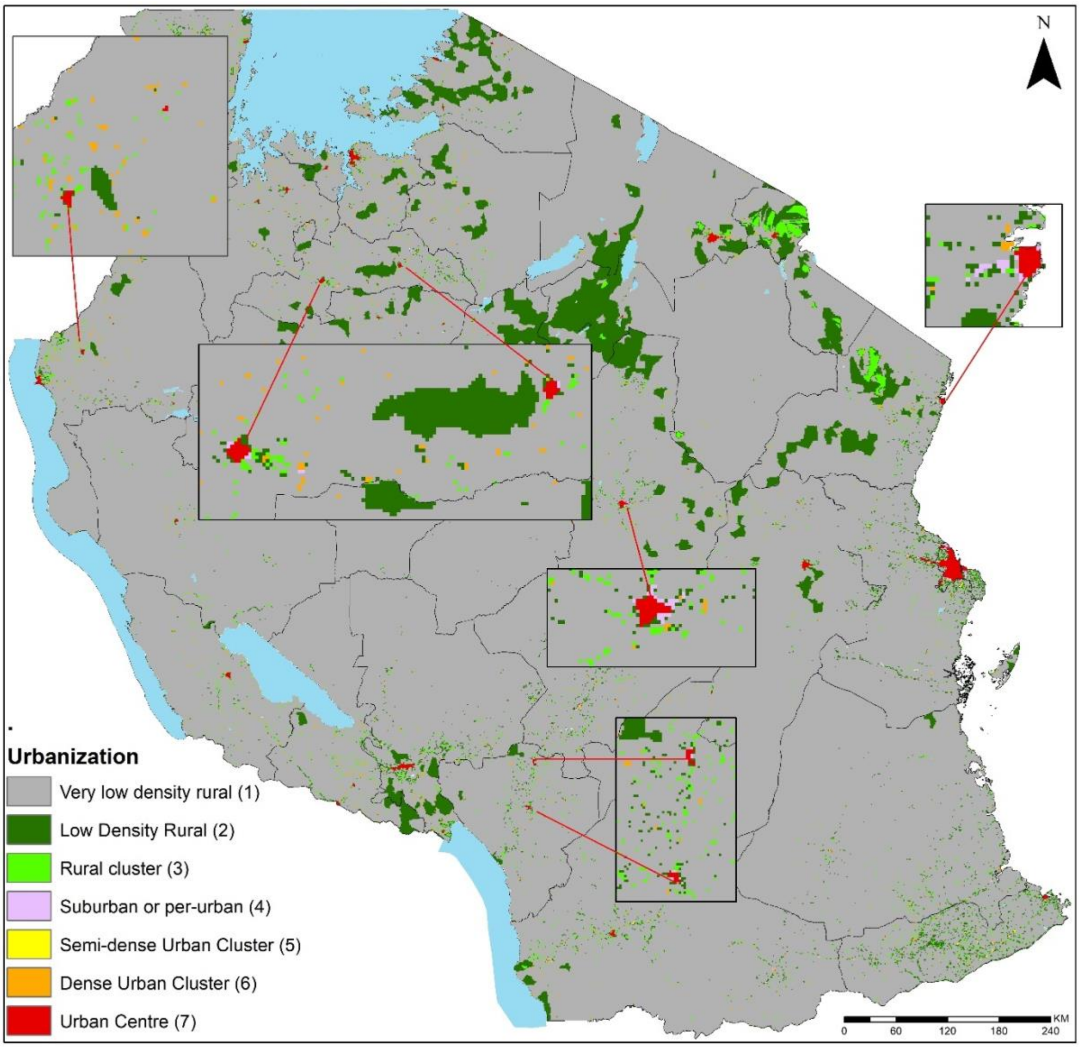


Figure S2. GHS-SMOD-derived urbanicity classifications based on satellite imagery

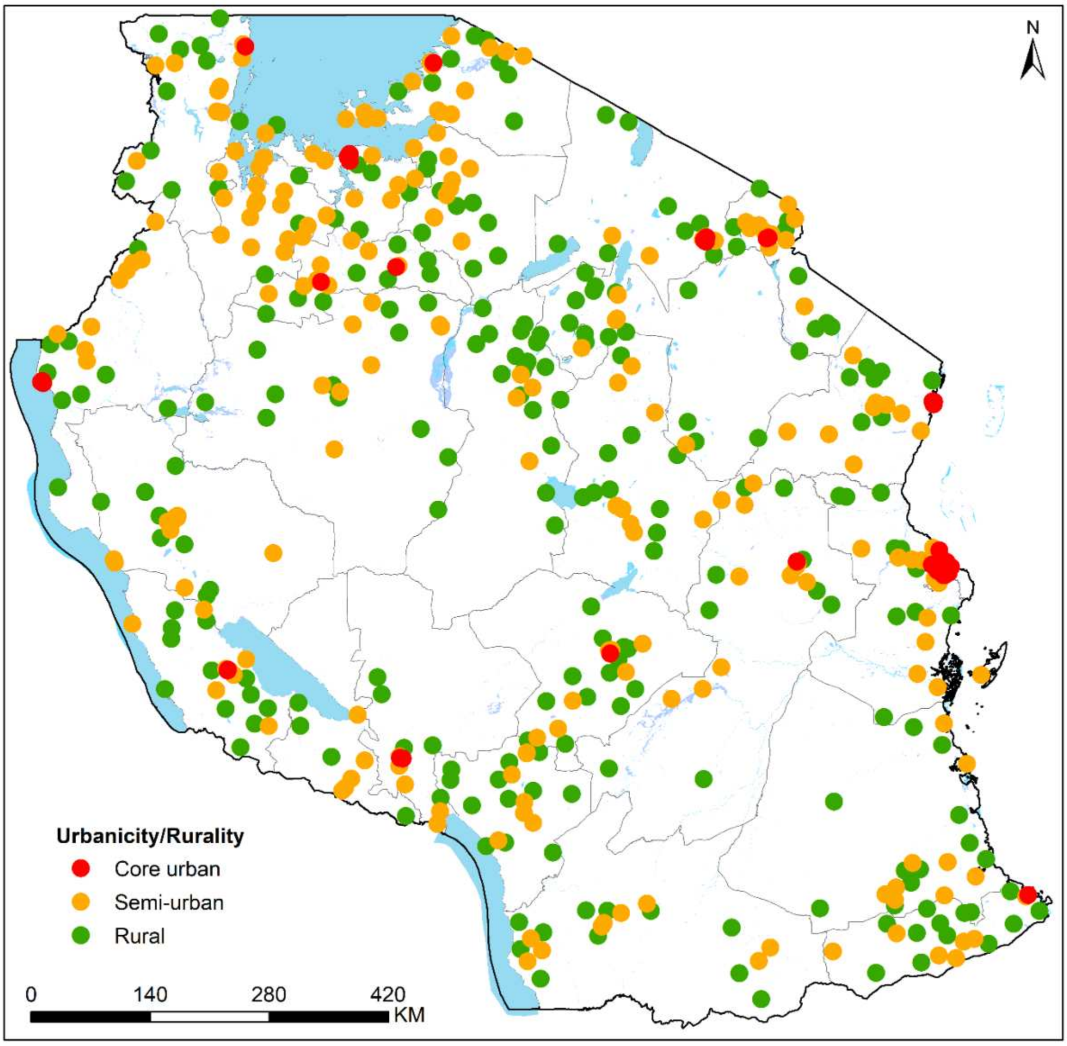


Figure S3. Travel time to the nearest hospital (n=236) in Tanzania in 2015 at 300m spatial resolution classified into 5 classes ranging from less than 30 minutes (green) to over 2 hours/120 minutes (red). The white areas are national parks/reserves that were considered as barriers except in presence of roads.

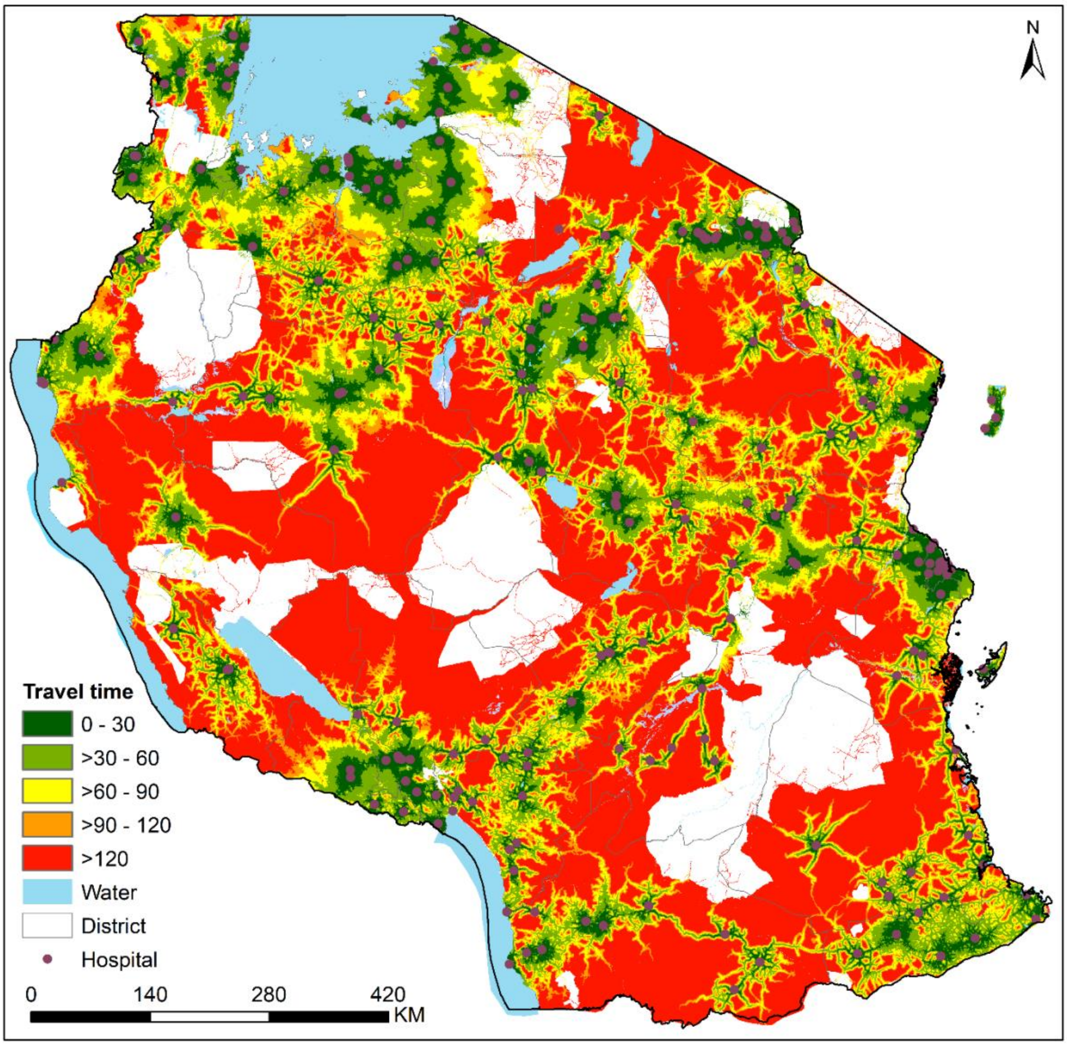
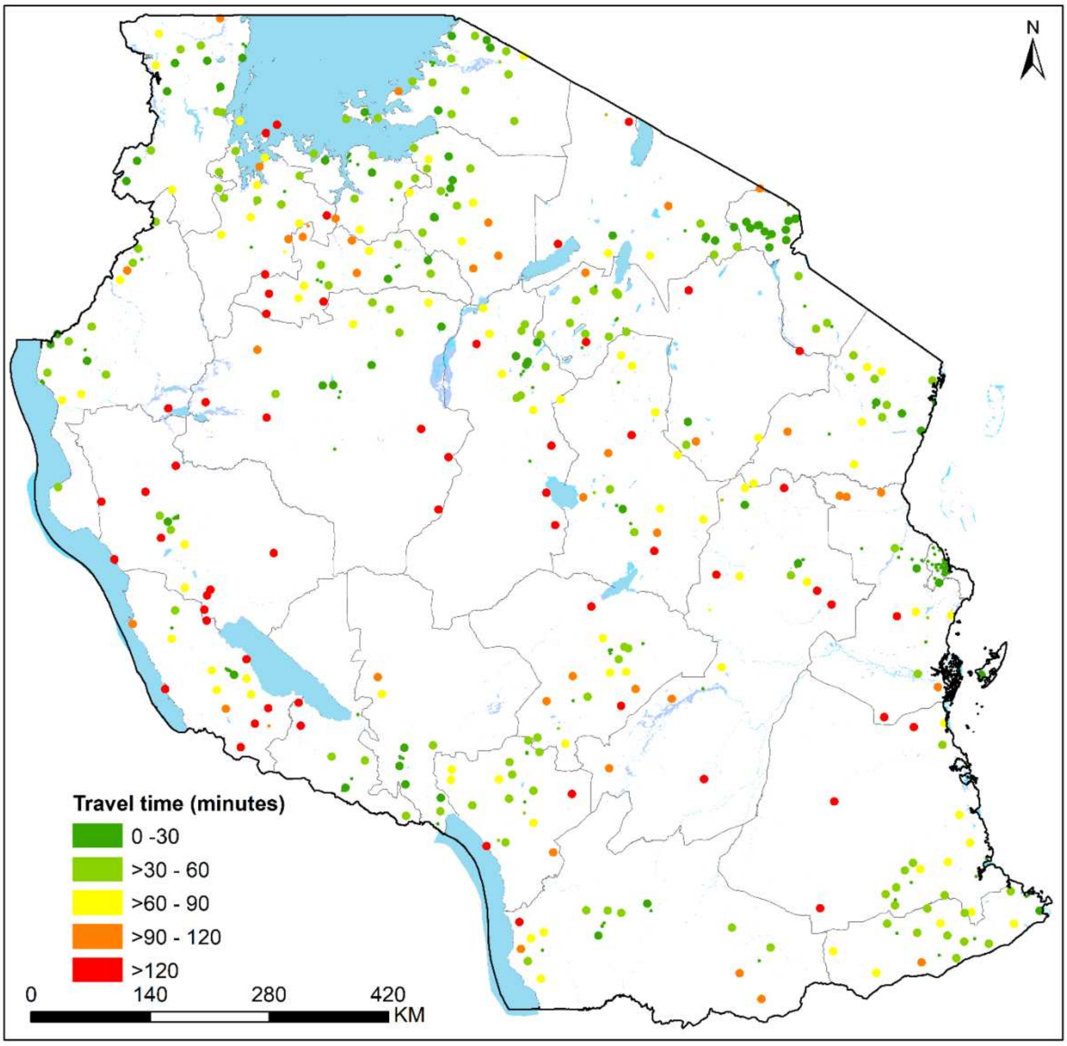


Figure S4. Travel time to the nearest hospital (n=236) in Tanzania in 2015 at cluster level classified into five classes ranging from less than 30 minutes (green) to +120 minutes (red)



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Supplementary file 2
Summary of variables used in analysis

LEVEL Dimension and variable	Response options	Availability Live births	 Stillbirths
GEOGRAPHIC ZONE			
Geographic zone (aggregation of regions into 8 zones, same as by DHS)	Western; Lake; Northern; Central; Southwest highlands; Southern Highlands; Southern; and Eastern	Yes	Yes
HOUSEHOLD CHARACTERISTICS			
Household wealth quintile (provided by DHS in the dataset)	Poorest; Poorer; Middle; Richer; Richest	Yes	Yes
Household size (mean number of members)	continuous	Yes	Yes
SOCIO-ECONOMIC CHARACTERISTICS OF THE WOMAN			
Maternal education and literacy	No education; Primary education/illiterate; Primary education/literate; Secondary or higher	Yes	Yes
Marital status at survey	Married or cohabiting; Not married/cohabiting	Yes	Yes
Maternal age group at time of birth (in years)	<20; 20-29; 30-49	Yes	Yes
Maternal decision-making about health - person who decides about woman's health care	Self (alone or in combination with others); Not the respondent at all (others)	Yes	Yes
Maternal relocation (fewer than 5 years lived in current residence at time of survey)	Yes; No	Yes	Yes
Maternal anaemia at survey (adjusted for altitude, smoking and current pregnancy)	Yes; No	Yes	Yes
Maternal mobile phone ownership	Yes; No	Yes	Yes
Ownership of health insurance	Yes; No	Yes	Yes
PREGNANCY AND HEALTH-SEEKING BEHAVIOUR			
Mode of childbirth	Vaginal; Caesarean	Yes	No
Multiple birth (twins or higher order multiples)	Yes; No	Yes	No
Birth order and preceding birth interval (months)	First child; 2nd or 3rd child with <24 months birth interval; 2nd or 3rd child with 24+ months birth interval; 4th or higher birth order child with <24 months birth interval; 4th or higher birth order child with 24+ months birth interval	Yes	No
Sex of child	Male; Female	Yes	No
Pregnancy wanted at the time of conception	Yes; No	Yes	No
Place of birth	Home; Lower lever facility; Hospital	Yes	No
Antenatal care during pregnancy	No ANC; 1-3 visits; 4 or more visits	Most recent only	No
Child weighed at birth	Yes; No	Most recent only	No
Child's birthweight category among babies who were weighed (in grams)	Low (<2500g); Normal (2500g-4000g); Macrosomia (>4000g)	Most recent only (if weighed)	No
OUTCOME			
Neonatal death (<30 days of live birth)	Yes; No	Yes	not applicable
Among neonatal deaths: Age of child at death in days	Continuous: 1 (day of birth) – 30	Yes (if neonatal death)	not applicable
Among neonatal deaths: Category of time of death	Day of birth; Day 2-7 (early); Day 8-30 (late)	Yes (if neonatal death)	not applicable
Among neonatal deaths if birth in health facility: Timing of neonatal death in relation to mother's discharge	Before mother discharged; After mother discharged	Yes (if facility delivery, most recent child & neonatal death)	not applicable
Stillbirth (death before birth after 7+ months of pregnancy)	Yes; No	not applicable	Yes
Perinatal death (death after 7+ months of pregnancy up to 7 days after birth)	Yes; No	Yes	Yes
EXPOSURE			
Residence according to DHS	Rural; Urban	Yes	Yes
GHS-SMOD exposure	Core urban; Semi-urban; Rural	Yes	Yes
Mean travel time from cluster to nearest hospital	continuous in minutes, continuous in hours	Yes	Yes
Category of travel time to nearest hospital	<2 hours; 2 hours or more	Yes	Yes

Supplementary file 3.
Distribution neonatal deaths by age at death and facility discharge, by urbanicity category

Neonatal deaths - distribution of age at death by urbanicity category (n=217)

	Overall (Tanzania mainland)	Core urban	Semi-urban	Rural	p-value
Category of age in days at death (column %)					
Day of birth	37.4%	26.9%	33.8%	45.3%	0.128
Days 2-7	48.3%	68.3%	46.8%	40.9%	
Days 8-30	14.3%	4.8%	19.4%	13.8%	
Number of days at death (mean and SE)	4.1 (0.38)	2.9 (0.39)	5.1 (0.70)	3.6 (0.58)	

Time of neonatal death (before of after discharge) among most recent live births in health facilities by urbanicity category

	Overall (Tanzania mainland)	Core urban	Semi-urban	Rural	p-value
Time of neonatal death					
Before discharge	44.9%	60.3%	27.2%	58.2%	0.045
After discharge	55.1%	39.7%	72.8%	41.8%	

Stillbirths: Early neonatal death ratio

Overall (Tanzania mainland)	Core urban	Semi-urban	Rural
0.85	0.52	0.93	0.94